U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-299 194

Removal of Trace Elements from Acid Mine Drainage

Hydroscience, Inc, Knoxville, TN

Prepared for

Industrial Environmental Research Lab -Cincinnati, OH

Apr 79

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/7-79-101
April 1979

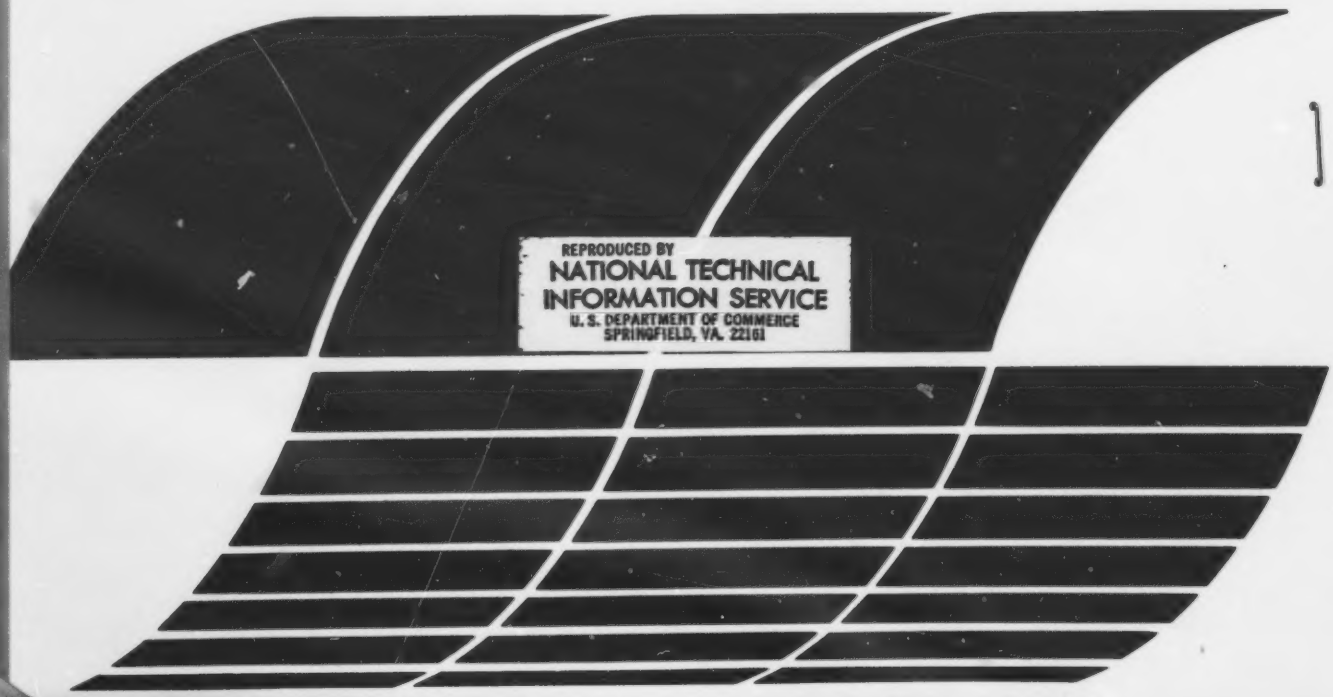
Research and Development

PB 299194

EPA

Removal of Trace Elements from Acid Mine Drainage

Interagency Energy/Environment R&D Program Report



REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects; assessments of, and development of, control technologies for energy systems; and integrated assessments of a wide range of energy-related environmental issues.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-79-101	2.
3. RECIPIENT'S ACCESSION NO. PB299194	
4. TITLE AND SUBTITLE: Removal of Trace Elements from Acid Mine Drainage	5. REPORT DATE: April 1979 issuing date
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): Roger C. Wilmoth, James L. Kennedy, Jack R. Hall, and Charles W. Stuewe	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Hydroscience, Inc. Knoxville, Tennessee 37919	10. PROGRAM ELEMENT NO. 1BB610
	11. CONTRACT/GRANT NO. 68-03-2568
12. SPONSORING AGENCY NAME AND ADDRESS: Industrial Environmental Research Lab. - Cinn, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED: Final 9/77-1/78
	14. SPONSORING AGENCY CODE: EPA/600/12

15. SUPPLEMENTARY NOTES

This was a cooperative in-house and contract-supported research effort.

16. ABSTRACT

Lime neutralization, reverse osmosis, and ion exchange were studied for their effectiveness in removing mg/l levels of ten specific trace elements from spiked acid mine drainage under typical operating conditions. The specified toxic materials were arsenic, boron, cadmium, chromium, copper, mercury, nickel, phosphorus, selenium, and zinc.

Treatment by lime neutralization was very effective in removing arsenic, cadmium, copper, mercury, nickel, and zinc, and relatively ineffective in removing boron and phosphorus. Reverse osmosis was very effective in rejecting arsenic, cadmium, chromium, copper, nickel, and zinc, and relatively ineffective in rejecting boron. The two-bed (strong acid-weak base) ion exchange system was very effective in removing all of the trace elements except phosphorus and boron. None of the three treatment methods was very effective in removing phosphorus.

Analysis for boron proved troublesome. Use of the standard nitric acid metals preservation methods was found to be inappropriate for samples requiring boron analysis.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Neutralizing Calcium oxides Drainage Acid treatment Trace elements	Reverse osmosis Ion exchange Lime neutralization Acid mine drainage Toxic materials	13B

18. DISTRIBUTION STATEMENT: Release to the Public	19. SECURITY CLASS *(This Report)*: Unclassified	21. NO. OF PAGES: 88
	20. SECURITY CLASS *(This page)*: Unclassified	22. PRICE: PCA05/MF A01

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979-657-060/1669 Region No. 5-11

EPA-600/7-79-101
April 1979

REMOVAL OF TRACE ELEMENTS FROM ACID MINE DRAINAGE

by

Roger C. Wilmoth and James L. Kennedy
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

and

Jack R. Hall and Charles W. Stuewe
Hydroscience, Inc.
Knoxville, Tennessee 37919

Contract No. 68-03-2568

Project Officer

Roger C. Wilmoth
Resource Extraction and Handling Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Industrial Environmental Research Laboratory, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report describes the results of studies conducted to determine the ability of lime neutralization, reverse osmosis, and ion exchange processes to remove ten inorganic trace elements from acid mine drainage. Results of this research should prove useful to both industry and regulatory agencies having problems with any of the ten pollutants in their discharges by providing possible treatment alternatives. For further information, please contact the Extraction Technology Branch of the Resource Extraction and Handling Division in Cincinnati.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

Lime neutralization, reverse osmosis, and ion exchange were studied for their effectiveness in removing mg/l levels of ten specific trace elements from spiked acid mine drainage under typical operating conditions. The specified trace elements were arsenic, boron, cadmium, chromium, copper, mercury, nickel, phosphorus, selenium, and zinc.

Treatment by lime neutralization was very effective in removing arsenic, cadmium, copper, mercury, nickel, and zinc, and relatively ineffective in removing boron and phosphorus. Reverse osmosis was very effective in rejecting arsenic, cadmium, chromium, copper, nickel, and zinc, and relatively ineffective in rejecting boron. The two-bed (strong acid-weak base) ion exchange system was very effective in removing all of the trace elements except phosphorus and boron. None of the three treatment methods was very effective in removing phosphorus.

Analysis for boron proved troublesome. Use of the standard nitric acid metals preservation methods was found to be inappropriate for samples requiring boron analysis.

CONTENTS

	Page
Foreword	iii
Abstract	iv
Figures	vi
Tables	vii
Acknowledgments	ix
1. Introduction	1
2. Conclusions	5
3. Recommendations	6
4. Treatment Studies	7
Background information	7
Trace element injection	7
Sample handling analysis	8
Lime neutralization	8
Reverse osmosis	20
Ion exchange	24
Waste treatment and disposal	35
References	36
Appendices	38
A. Discussion of Analytical Results	38
Problems encountered	38
Analytical interpretation	39
Review of quality assurance program	40
Intralaboratory quality control program	40
B. Outline of Analytical Methods and Instrumentation	49
C. Individual Analytical Data	52
Glossary	74

FIGURES

Number		Page
1	Schematic flow diagram for the EPA neutralization facility.	12
2	The effect of pH on trace element concentration in the neutralization process effluent.	15
3	Flow diagram for the 4000-gpd spiral-wound reverse osmosis unit.	21
4	Schematic flow diagram of EPA 2-resin ion exchange unit.	26
5	Photograph of the ion exchange installation at Crown. . .	27
6	Trace element trends throughout the cation service cycle	31
7	Trace element trends throughout the anion service cycle	32
8	Conventional pollutant trends throughout the cation service cycle	33
9	Conventional pollutant trends throughout the anion service cycle	34
A-1	Example of daily standard curve	42
A-2	Example of blind split analysis certificate	45
A-3	Example of spiked sample analysis certificate	46
A-4	Example of precision control chart.	47
A-5	Example of a blind standard analysis certificate.	48

TABLES

Number		Page
1	Selected Mine Drainage Analyses.	3
2	Selected Pollutants and Desired Concentrations for Treatability Study	4
3	Summary of Optimum Removal of Trace Elements	5
4	Crown Raw Water Quality During Trace Element Study	9
5	Trace Element Levels in Spiked AMD	10
6	Neutralization Operational Data Summaries for Trace Element Study.	13
7	Summary of Lime Neutralization Water Quality Analyses	14
8	Detailed Summary of Lime Neutralization Chemical Analyses	16
9	Mean Operating Parameters for Crown Spiral-Wound Reverse Osmosis Study.	22
10	Reverse Osmosis Water Quality Summary.	23
11	General Specifications for EPA Ion Exchange Treatment Unit	28
12	Average Values for the Ion Exchange Operating Parameters	29
13	Ion Exchange Water Quality Summary	30
A-1	Example of Precision Data (Water Sample Analysis for Mercury)	43
A-2	Example of Accuracy Data for Phosphorus.	44
B-1	Applicable Analytical Methodology.	51

TABLES (Continued)

Number		Page
C-1	Trace Element Pollutant Anlayses for Lime Neutralization	52
C-2	Conventional Pollutant Chemical Analyses for Lime Neutralization	58
C-3	Material Balance for Lime Neutralization Study	64
C-4	Reverse Osmosis Trace Element Analyses	65
C-5	Reverse Osmosis Conventional Pollutant Analyses.	67
C-6	Material Balance for Reverse Osmosis Study	69
C-7	Ion Exchange Trace Element Analyses.	70
C-8	Ion Exchange Conventional Pollutant Analyses	72

ACKNOWLEDGMENTS

The cooperation and participation of the Resource Extraction and Handling Division personnel, including Ronald D. Hill, Eugene F. Harris, Robert B. Scott, Harry L. Armentrout, Robert M. Michael, Daniel L. Light, Loretta J. Davis, James L. Shaffer, Jessie R. Burdett, and Barbara A. Cappel was important to the completion of the study. The assistance of Kenneth A. Crabtree of EPA Procurement Division was instrumental to the timely completion of the research effort.

Special thanks are extended to J. Randolph Lipscomb for his onsite supervision of the research program. Our appreciation is also extended to Dr. Anna M. Yoakum and Barry Stephenson of Stewart Laboratories for their cooperation and rapid response to the needs of the analytical program. The study was made possible by the assistance and cooperation of Consolidation Coal Company. We wish to specifically thank Dr. Gerald Barthauer, Mike O'Brien, Ray Henderson, Mike Ryan, and Hershel Travis for their helpfulness.

SECTION 1

INTRODUCTION

In recent years, the U. S. Environmental Protection Agency (EPA) through contracts, grants, and in-house research has addressed the problem of treating acid mine drainage (AMD) to recover water for reuse or discharge into streams. As part of this program, the EPA established the Crown Mine Drainage Control Field Site, located near Morgantown, West Virginia, to study the treatability of predominately ferrous iron AMD.

Treatment methods for AMD involve either neutralization and precipitation, reverse osmosis, ion exchange, or combinations of these. The most common treatment method for AMD discharges is neutralization using lime (1-2). By this process, dissolved iron, manganese, aluminum, and other metal ions are precipitated at an elevated pH and separated as a sludge for disposal. Oxidation of iron from the ferrous to ferric state and coagulant addition are used to improve the effluent quality (2). Other alkaline materials such as limestone (calcium carbonate), sodium carbonate, and sodium hydroxide can be used instead of lime.

In addition to neutralization, reverse osmosis and ion exchange have been reported as AMD treatment methods by the EPA and others (3-4). In reverse osmosis (RO), water molecules from the AMD are driven by pressure through semi-permeable membranes leaving behind most of the dissolved salts as a concentrated waste effluent (brine). Rejection rates of 99% of the salts have been reported from EPA studies on various AMD streams (5-6). In other studies, AMD was effectively demineralized in the two-resin ion exchange pilot system in use at the Crown site (7).

All these previous EPA studies emphasized the overall applicability of the treatment method, operational limitations, cost, and conventional parameters of effluent quality (3). These parameters included iron, manganese, suspended solids, and aluminum concentrations and pH.

The presence of trace elements in acid mine drainage (AMD) has received little attention in the past; however, recent cognizance has prompted the research community to address the situation. AMD offers a favorable medium for existence of trace elements because many are acid-soluble and are leached from strata associated with the mining process. Some trace elements are on the EPA list of Priority Pollutants.

The purpose of this study was to determine the effectiveness of lime neutralization, reverse osmosis, and ion exchange treatment processes in removing several of the trace elements. The study was conducted at the EPA Crown Field Site, where appropriate concentrations of trace elements could be

injected into a moderately-acid AMD stream to simulate the field situation.

The selection of the parameters to be studied and their respective concentrations was made on the basis of levels found in mine discharges. Table 1 illustrates the matrix of data used in the selection. These choices are summarized in Table 2. Eight of the 10 are listed by EPA as toxic substances. For this study the 10 compounds were combined in one concentrated bulk solution and were continuously injected into the AMD feed streams to the neutralization, reverse osmosis, and ion exchange processes to form the desired concentrations. Some precipitation problems were encountered during lab-scale concentrate preparation, necessitating substituting different compound forms of two elements and eliminating lead from the original study list. Table 2 contains the final choice of compounds.

TABLE 1. SELECTED MINE DRAINAGE ANALYSES
(mg/l)

Pollutant Source	pH	Al	As	B	Be	Ca	Cd	Chl	Co	Cr	Cu	Cyn	Fe	F	Hg	K	Mg	Mn	Na	Ni	P	Pb	Se	SO_4	Sr	Te	Ti	Zn
Iron ore	5					260		120		0.01	1.0	0.02	180		2.0		120	18	15	0.1		0.1			120	0.6		8.0
Copper	3.5			2.0			1.3		2.0		90		2000		7.17			100		0.2	0.15		0.04					
Lead/zinc	8.1						0.02	57		0.1				1.8								4.0		63				0.7
Lead/zinc	3.0						0.06	220			0.04		2.5	0.5				57			0.08	0.3		780				38
Gold	6		0.08	0.2		87	0.03	1.8			0.05		25	2.1		11	80	12	80	0.1		0.8		1200	0.8	0.1		7.3
Silver	8			0.1		45		1.2					2.0	0.1	1,000	15	32	6.3	12	0.00		0.2	0.13	340				
Bauxite	2.8	88											64	0.1				7.7		0.3				800				0.8
U/Va/V		0.5	0.03		0.01	120							15				48	0.3									1.1	0.03
Platinum				0.01		95		160					0.3	3.0		11	26		140			0.01	0.8	270				0.03
Coal mining-east[9]		530											9300					92		5.6				9700				13
Coal mining-west[9]	2.4	43											350					7.3		0.7				2400				1.5
AMD[10]	2.8	62	22				1.0				128		800					19		0.5		0.5		3800				250
AMD[11]	2.6	240	0.9				0.9				18		610					9.0		0.5		0.9		3310				23
Crown AMD	5.0	15				370							300				110	6	180					3000				
Chosen Levels	5.0	15	2.0	1.0		370	1.0	10	1.0	0.4	5.0	0.5	300	2.	2.5	10	110	6.0	180	0.5	1.0	1.0	0.8	3000	1.0	0.5	1.0	5.0

TABLE 2. SELECTED POLLUTANTS AND DESIRED CONCENTRATION FOR TREATABILITY STUDY

Pollutant	Concentration, mg/l	Compound used
Arsenic	2.0	Arsenic pentoxide
Boron	1.0	Boric acid
Cadmium	1.0	Cadmium sulfate
Chromium	0.4	Chromium chloride
Copper	5.0	Cupric chloride
Mercury	0.5	Mercuric chloride
Nickel	0.5	Nickelous sulfate
Phosphorus	1.0	Sodium phosphate
Selenium	0.8	Selenous acid
Zinc	5.0	Zinc chloride

SECTION 2

CONCLUSIONS

The removal effectiveness of each of the three processes (lime neutralization, reverse osmosis, and ion exchange) is summarized in Table 3. The neutralization process appeared to be the logical process choice, because of cost, for trace material removal for all the elements studied except boron and phosphorus. None of the three processes was effective on boron and phosphorus. Although ion exchange and reverse osmosis were slightly more effective overall than lime neutralization, the cost of the processes and need for subsequent waste treatment offset their slight advantage in removal effectiveness.

TABLE 3. SUMMARY OF OPTIMUM REMOVAL OF TRACE ELEMENTS

Trace element	Typical influent conc., mg/l	Optimum effluent concentration, mg/l			
		Lime neutralization pH 7-9 range	Lime neutralization pH 10-12 range	Reverse osmosis	Ion exchange
Arsenic	2.3	0.04 @ pH 9	0.02 @ pH 10	0.01	0.52
Boron	2.2	2.2 @ pH 7	1.45 @ pH 12	0.88	0.58
Cadmium	0.9	0.06 @ pH 8	0.01 @ pH 10	0.006	0.001
Chromium	0.06	0.04 @ pH 7	0.04 @ pH 12	0.01	0.01
Copper	6.2	0.11 @ pH 9	0.05 @ pH 10	0.01	0.03
Mercury	0.5	0.01 @ pH 8	0.01 @ pH 9	0.06	0.001
Nickel	0.7	0.06 @ pH 9	0.06 @ pH 9	0.01	0.02
Phosphorus	1.5 to 10	2.3 @ pH 9	1.09 @ pH 12	0.32	no removal
Selenium	1.2	0.05 @ pH 7	0.15 @ pH 12	0.11	0.09
Zinc	6.3	0.11 @ pH 9	0.09 @ pH 12	0.06	0.03

SECTION 3

RECOMMENDATIONS

The apparent inability of all the processes, and specifically the neutralization process, to remove phosphorus needs further investigation.

Similarly, the loss of mercury in the reverse osmosis process should be studied.

An analytical method for determination of boron should be developed for samples preserved with the EPA nitric acid technique.

SECTION 4

TREATMENT STUDIES

BACKGROUND INFORMATION

Lime neutralization, reverse osmosis (RO), and ion exchange (IE) were studied at the EPA Crown Field Site to determine their effectiveness in removing the 10 trace elements of interest. EPA awarded a contract to Hydroscience, Inc., a subsidiary of Dow Chemical, to provide analytical services for the trace element analyses and to provide technical assistance. The processes had been thoroughly studied by EPA (1-2) for removal of the conventional parameters of interest in AMD (e.g., acidity, iron, manganese, aluminum, magnesium, sodium, sulfate, etc.). For this study, all processes were operated in the mode optimum for pollutant removal, which is not necessarily the optimum mode for feasibility. The neutralization, RO, and IE systems were therefore not optimized for cost but functioning under conditions shown in previous studies to be most effective for achieving the highest effluent quality.

TRACE ELEMENT INJECTION

It was not known previous to the study if the trace elements of interest were naturally occurring in the AMD at the Crown pilot plant. The Crown AMD was pumped from an abandoned deep mine in the Pittsburgh coal seam, located approximately 85 m (280 ft) below the surface. It was assumed that the trace elements would have to be added to the AMD to achieve the desired concentrations. This assumption proved to be generally valid except for boron, phosphorus, and nickel, which were shown during the study (Table 4) to be present in the raw unspiked AMD. The background trace element levels were not considered in designing the spiking system because they were unknown at the start of the study.

The desired trace element concentrations were obtained in the AMD by continuous injection via chemical metering pumps of a concentrated spiking solution into the AMD feed line to the process being studied. The spiking solution was prepared in bulk amounts in a 2500-liter polyethylene tank, which was equipped with a mixer. To minimize stratification, the mixer operated on a pulsed basis, i.e., on one minute of every 10. Continuous mixer operation was not desirable because of excessive evaporative loss and concern for gross concentration changes. The 2500-liter tank was equipped with a wooden cover to reduce evaporation and splashing. Table 5 summarizes the desired level of pollutant concentration and the actual concentrations achieved for each process influent. The desired levels conformed very well to the achieved levels for all parameters except phosphorus, which proved to be intermittently present

in the Crown source. Extremely high variations in phosphorus content were observed in the raw AMD and remain largely unexplained. The phosphorus variation was prominent only during the neutralization phase of the study when influent values above 40 mg/l were observed.

Even though the reverse osmosis and ion exchange studies were run concurrently, the spiked feed for the two studies, as analyzed for the trace elements, differed. The concentrations of all elements except phosphorus were lower in the feed for the RO study. This was due to a small difference in flowrates of the spiking solution from the two metering pumps. A problem is apparent, however, in the RO process where mercury was consistently analyzed in the feed at about 50% of the level measured in the feed to the IE process. Since the RO feed sample was taken downstream of the cartridge filter which was downstream of the sulfuric acid addition point, partial removal by the filter of mercury as mercuric sulfate was suspected. This is discussed further later.

The individual analytical data for each sample are presented in Appendix C.

SAMPLE HANDLING ANALYSIS

Samples from all of the treatment methods were handled in a similar manner. Portions of the samples were immediately analyzed on-site, without sample preservation, for pH, acidity, alkalinity, calcium, magnesium, sodium, ferrous iron, total iron, aluminum, manganese, suspended solids, specific conductance and sulfate.

The remaining samples, except for the sludge samples, were preserved and shipped off-site for analysis. EPA Methods (1976) were used for all the metal determinations. The EPA Methods manual (12) requires sample preservation with nitric acid; however, it was discovered part way through the lime neutralization study that nitrates interfere with the determination of boron and many of the boron data were lost in this manner. From that time forward, additional unpreserved samples were collected and shipped off-site for the boron analysis. This problem is discussed in further detail in Appendix A.

LIME NEUTRALIZATION

Background

Lime neutralization represents the Best Practical Technology (BPT) for acid mine drainage treatment. A schematic of the lime neutralization process utilized at the Crown facility is shown in Figure 1. The neutralization system consists of two identical treatment processes that operated at 0.9-liter/sec AMD flow each. Twin chemical metering pumps injected 100 ml/min each of bulk trace element solution into the separate treatment lines to achieve the desired final concentrations shown in Table 5. The lime neutralization process investigated trace element removal effectiveness as a function of pH. Two pH levels were studied at one time. Approximately seven days were required to characterize a particular pH level (i.e., two days to achieve

TABLE 4. CROWN RAW WATER QUALITY
DURING TRACE ELEMENT STUDY (9/19/77-10/12/77)

Parameter	Unit	Mean	Maximum	Minimum	Standard deviation
Acidity as $CaCO_3$	mg/l	440	660	300	82
Alkalinity	mg/l	26	55	0	13
Aluminum	mg/l	6.6	14	2.5	2.5
Calcium	mg/l	350	390	310	18
Iron, ferrous	mg/l	150	200	130	15
Iron, total	mg/l	160	200	130	14
Magnesium	mg/l	100	110	90	5.3
Manganese	mg/l	5.0	6.2	3.7	.46
pH	pH	5.2	5.6	4.7	.21
Sodium	mg/l	350	410	300	20
Specific conductance	µmhos/cm	2610	2950	2300	153
Sulfate	mg/l	2380	2660	2180	104
Total dissolved solids	mg/l	3350	3640	3110	124
Arsenic	mg/l	0.014	0.03	0.01	0.006
Boron	mg/l	0.61	0.9	0.3	0.19
Cadmium	mg/l	0.0010	0.002	0.001	0.0002
Chromium	mg/l	0.040	0.10	0.02	0.019
Copper	mg/l	0.022	0.04	0.01	0.010
Mercury	mg/l	<0.00021	0.0004	<0.0002	0.00004
Nickel	mg/l	0.191	0.24	0.13	0.094
Phosphorus	mg/l	7.89	41.0	0.48	10.53
Selenium	mg/l	<0.0011	0.002	<0.001	0.0003
Zinc	mg/l	0.280	0.358	0.206	0.037

TABLE 5. TRACE ELEMENT LEVELS IN SPIKED ACID MINE DRAINAGE
(mg/l)

Element	Desired level	Actual level achieved (means)		
		Lime neutralization	Reverse osmosis	Ion exchange
Arsenic	2.0	1.96	2.29	2.47
Boron	1.0	2.36	2.01	2.38
Cadmium	1.0	0.90	0.83	0.95
Chromium	0.4	0.55	0.54	0.63
Copper	5.0	5.30	6.18	7.27
Mercury	0.5	0.50	0.28	0.72
Nickel	0.5	0.67	0.74	0.86
Phosphorus	1.0	9.85	1.50	1.47
Selenium	0.8	0.95	1.17	1.34
Zinc	5.0	5.65	6.25	7.44

equilibrium and five days data collection). The study spanned pH levels in single pH increments between pH 7 and pH 12. Process A was operated at pH 11, 9, and 7 in that order while Process B was operated at pH 10, 8, and 12. No sludge recycling was used during this study.

A coagulant (Dowell M-144 anionic type) was injected into each flow stream just prior to the clarifier at approximately a 5-mg/l rate to achieve optimal clarifier performance. Samples were taken of the raw AMD, spiked AMD A, spiked AMD B, product A, and product B, sludge A, and sludge B. These samples were collected automatically by composite samplers. Samples were sent for analysis twice per day for a daily total of 14 separate samples from both processes, and 168 samples from the entire neutralization study.

Results

The operational data are summarized in Table 6 as a function of pH and indicate normal trends except for slightly high lime usage at pH 9. These sorts of anomalies are not unusual for neutralization processes applied to AMD treatment.

Analyses for the trace elements and conventional parameters are summarized as a function of pH in Table 7. Significant removals were observed for all elements except boron and phosphorus. The inability to remove phosphorus below 1 mg/l was very unexpected. Phosphorus removal by lime addition is state-of-the-art technology in tertiary sewage treatment systems. Trace element removal is illustrated graphically in Figure 2. Individual sample analyses are given in Appendix C.

A more detailed breakdown of trace element data is presented in Table 8, including sludge analyses. Sludge analysis is very difficult and obtaining accurate mass balances are even more difficult (material balances are shown in Table C-3 of the Appendix). Some interesting phenomena appear in the sludge data. For example, sludge trace element levels are significantly higher at pH 7 than at any higher pH. This may be partly due to the relatively low percentage of the conventional pollutants (magnesium, iron, manganese, etc.), which more completely precipitate at higher pH's and thus the ratio of concentrations of trace elements to the conventional elements in the sludge is higher. Since conventional analyses were not made on the sludge, this is difficult to verify. Means of the conventional water analyses are also summarized in Table 8. The only conventional parameter that did not meet or exceed current effluent guidelines standards was manganese at pH 8 and below.

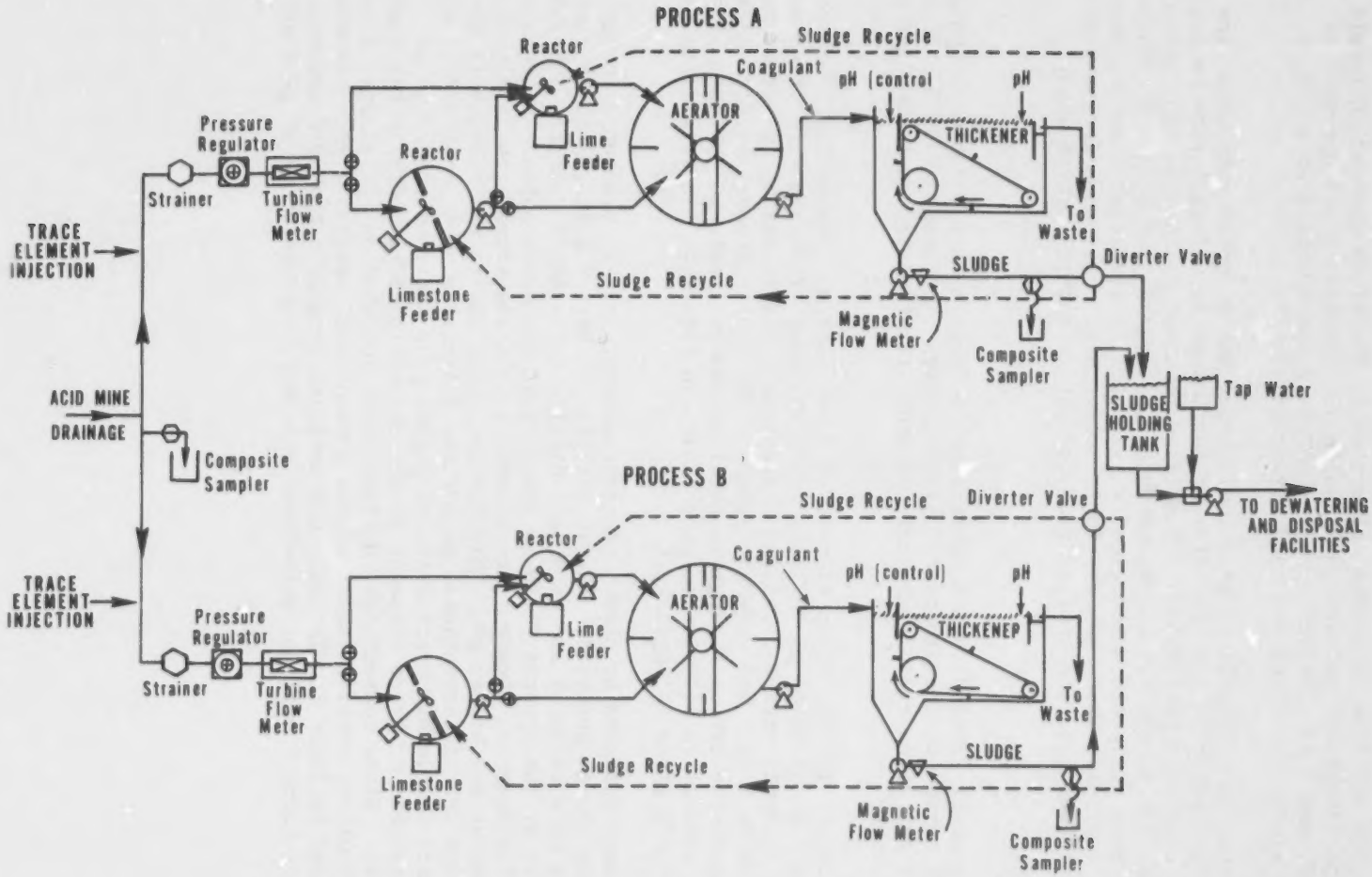


Figure 1. Schematic flow diagram for the EPA neutralization facility.

TABLE 6. NEUTRALIZATION OPERATIONAL DATA SUMMARIES FOR TRACE ELEMENT STUDY

Item	Mean value					
Effluent pH	7.0	8.0	9.1	10.1	11.0	12.1
Neutralizer usage, kg/cu m	0.28	0.43	0.82	0.85	0.91	2.63
Neutralizer usage, lb/1000 gal	2.3	3.6	6.8	7.1	7.6	22
Neutralizer usage, g/cu m/ppm influent acidity	0.6	1.2	2.1	1.8	2.0	5.4
Cost, cents/1000 gal*	4.1	6.3	12	12	13	39
Cost, cents/cu m	1.1	1.7	3.1	3.3	3.5	10
Cost, cents/10^3cu m/ppm influent acidity	2.4	4.4	8.0	7.0	7.7	21
Utilization efficiency, percent	132	71	39	45	44	51
Stoichiometric factor (influent acidity)	0.8	1.5	2.8	2.5	2.7	7.3
Sludge to waste, % of influent AMD	10	8.7	10	9.7	10	14
Dry solids to waste, lb/1000 gal	9.9	4.6	18	8.7	13	17
Dry solids to waste, kg/cu m	1.2	0.5	2.1	1.0	1.6	2.0
Underflow solids, percent	1.2	0.6	2.1	1.1	1.5	1.5
Effluent turbidity, JTU	24	11	10	7	7	3
Reactor suspended solids, mg/l	380	530	1130	1310	1440	2500
Effluent suspended solids, mg/l	25	12	24	12	15	15

*Lime cost $38.58/tonne ($35.00/ton).

TABLE 7. SUMMARY OF LIME NEUTRALIZATION WATER QUALITY ANALYSES

Parameter	Typical spiked influent	Nominal pH of effluent					
		7	8	9	10	11	12
Actual median pH	5.0	7.0	7.9	8.9	10.0	10.9	12.2
Arsenic	1.96	0.10	0.05	0.04	0.02	0.03	0.02
Boron	2.36	2.25	-	-	1.68	1.90	1.45
Cadmium	0.90	0.18	0.06	0.08	0.01	0.01	0.01
Chromium	0.54	0.04	0.07	0.07	0.06	0.05	0.04
Copper	5.30	0.30	0.16	0.11	0.05	0.06	0.08
Mercury	0.50	0.02	0.01	0.01	0.01	0.02	0.01
Nickel	0.66	0.34	0.18	0.08	0.06	0.06	0.06
Phosphorus	9.83	3.81	2.67	2.30	2.88	3.56	1.09
Selenium	0.94	0.05	0.06	0.16	0.28	0.39	0.15
Zinc	5.65	1.01	0.23	0.11	0.07	0.11	0.09
Acidity	440	13	-0-	-0-	-0-	-0-	-0-
Alkalinity	15	47	36	44	50	90	1220
Aluminum	8.9	0.40	0.33	0.31	0.40	0.40	0.23
Calcium	350	470	460	480	530	610	970
Iron, ferrous	150	0.25	-0-	-0-	-0-	-0-	-0-
Iron, total	160	1.4	0.65	0.33	0.40	0.35	0.05
Magnesium	100	100	96	65	25	5.0	0.06
Manganese	5.1	3.7	2.5	0.19	0.06	0.06	0.05
Sodium	350	340	340	330	340	340	340
Specific conductance	2600	2630	2540	2430	2840	2840	5960
Sulfate	2380	2400	2020	2160	2250	2340	3230
Total dissolved solids	3340	3310	3160	3040	3160	3290	4540

All units are mg/l except for pH and specific conductance (μmhos/cm).

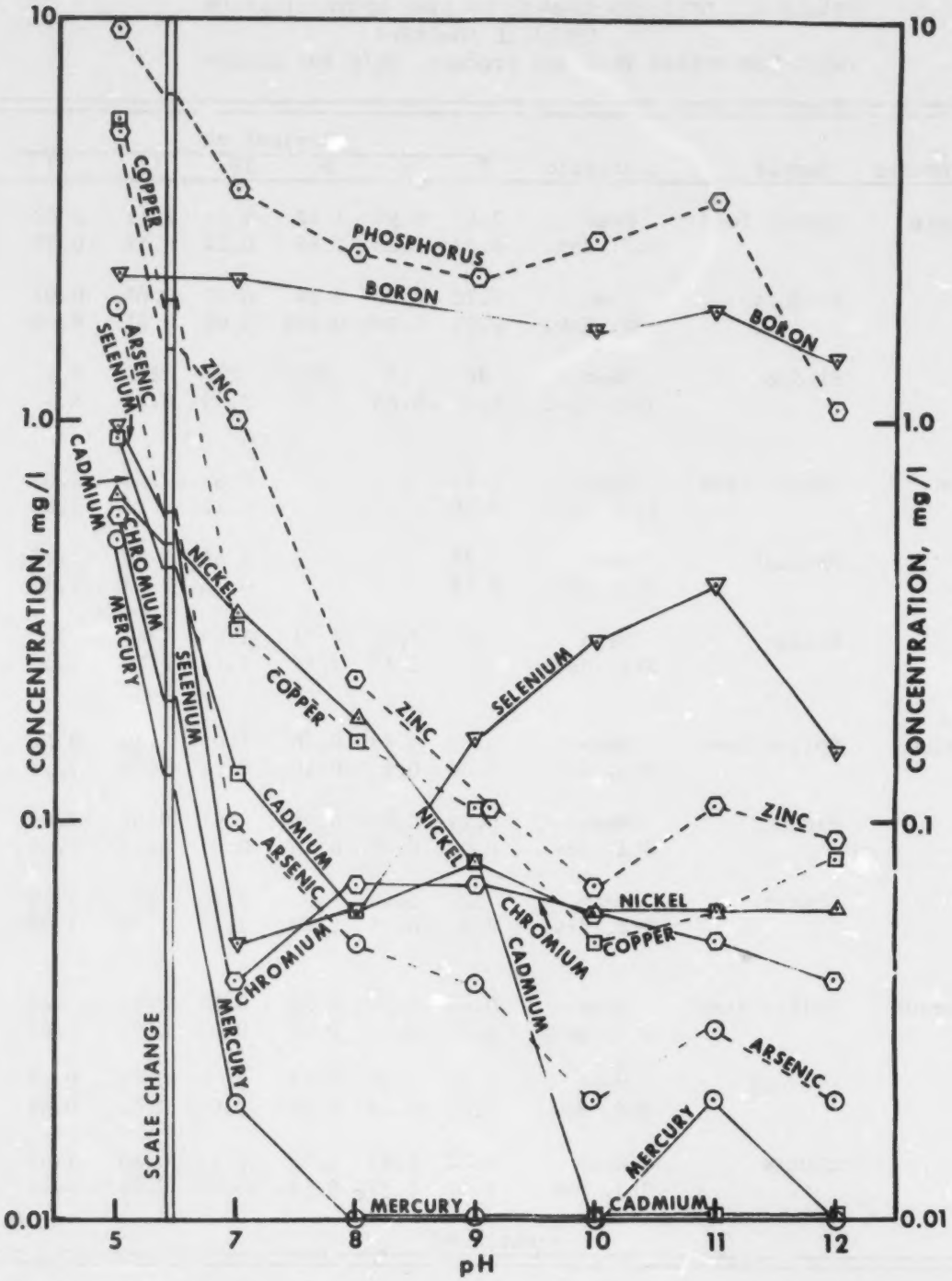


Figure 2. The effect of pH on trace element concentration in the neutralization process effluent.

TABLE 8. DETAILED SUMMARY OF LIME NEUTRALIZATION CHEMICAL ANALYSES
(mg/l for spiked feed and product, µg/g for sludge

Parameter	Sample	Statistic	Nominal pH 7	8	9	10	11	12
Arsenic	Spiked feed	Mean	2.01	1.97	1.88	1.75	2.11	2.02
		Std. dev.	0.14	0.26	0.86	0.24	0.18	0.15
	Product	Mean	0.10	0.05	0.04	0.02	0.03	0.02
		Std. dev.	0.01	0.008	0.005	0.01	0.01	0.004
	Sludge	Mean	46	13	29	13	23	8.5
		Std. dev.	8.2	9.88	2.71	3.05	3.41	4.5
Boron	Spiked feed	Mean	2.45	-	-	2.55	2.08	2.35
		Std. dev.	0.56			0.21	0.21	0.60
	Product	Mean	2.25	-	-	1.68	1.90	1.45
		Std. dev.	0.54			0.13	0.27	0.47
	Sludge	Mean	17	4.01	4.74	1.92	5.44	12
		Std. dev.	3.7	2.17	2.41	1.12	2.79	3.3
Cadmium	Spiked feed	Mean	0.67	0.86	0.86	1.03	1.30	0.66
		Std. dev.	0.08	0.15	0.19	0.06	0.06	0.12
	Product	Mean	0.18	0.06	0.08	0.01	0.01	0.01
		Std. dev.	0.02	0.01	0.16	0.01	0.01	0.02
	Sludge	Mean	12	6.86	15	8.48	15	3.20
		Std. dev.	2.3	6.63	2.80	2.12	1.49	1.00
Chromium	Spiked feed	Mean	0.49	0.58	0.56	0.53	0.65	0.46
		Std. dev.	0.05	0.07	0.06	0.08	0.06	0.07
	Product	Mean	0.04	0.07	0.07	0.06	0.05	0.04
		Std. dev.	0.01	0.04	0.03	0.01	0.01	0.01
	Sludge	Mean	8.82	2.83	5.82	2.84	4.50	1.67
		Std. dev.	1.6	1.79	0.53	0.62	0.54	0.56

(continued)

TABLE 8 (continued)

Parameter	Sample	Statistic	Nominal pH 7	8	9	10	11	12
Copper	Spiked feed	Mean	5.29	5.40	5.18	4.80	6.15	5.00
		Std. dev.	0.47	0.84	0.58	0.35	0.18	0.73
	Product	Mean	0.30	0.16	0.11	0.05	0.06	0.08
		Std. dev.	0.06	0.02	0.01	0.01	0.03	0.03
	Sludge	Mean	115	31	72	31	56	37
		Std. dev.	21	25	8.49	7.81	6.80	44
Mercury	Spiked feed	Mean	0.50	0.48	0.47	0.47	0.60	0.47
		Std. dev.	0.04	0.06	0.09	0.02	0.05	0.02
	Product	Mean	0.02	0.014	0.009	0.009	0.020	0.010
		Std. dev.	0.002	0.003	0.002	0.003	0.010	0.006
	Sludge	Mean	7.55	2.54	4.89	2.03	3.90	1.78
		Std. dev.	1.42	1.91	0.45	0.53	0.47	0.76
Nickel	Spiked feed	Mean	0.66	0.68	0.67	0.63	0.74	0.61
		Std. dev.	0.05	0.08	0.07	0.03	0.04	0.09
	Product	Mean	0.34	0.18	0.08	0.06	0.06	0.06
		Std. dev.	0.04	0.05	0.05	0.01	0.01	0.01
	Sludge	Mean	6.57	3.46	9.10	4.16	7.07	3.11
		Std. dev.	0.77	2.81	0.73	1.02	0.61	1.96
Phosphorus	Spiked feed	Mean	7.03	5.88	5.66	17	17	6.55
		Std. dev.	2.34	2.70	2.76	16	17	2.49
	Product	Mean	3.81	2.67	2.30	2.88	3.56	1.09
		Std. dev.	1.13	1.21	1.23	1.64	2.03	0.46
	Sludge	Mean	56	14	42	19	34	9.04
		Std. dev.	17	5.92	5.81	3.82	10	2.69

(continued)

TABLE 8 (continued)

Parameter	Sample	Statistic	Nominal pH 7	8	9	10	11	12
Selenium	Spiked feed	Mean	1.01	0.95	0.84	0.80	1.06	1.01
		Std. dev.	0.10	0.18	0.13	0.05	0.10	0.09
	Product	Mean	0.05	0.06	0.16	0.28	0.39	0.15
		Std. dev.	0.01	0.02	0.02	0.05	0.04	0.02
	Sludge	Mean	16	4.08	9.38	2.96	4.79	3.38
		Std. dev.	2.45	1.85	1.16	0.52	0.60	1.91
Zinc	Spiked feed	Mean	5.61	5.66	5.40	5.32	6.57	5.32
		Std. dev.	0.60	0.70	0.56	0.21	0.32	1.00
	Product	Mean	1.01	0.23	0.11	0.07	0.11	0.09
		Std. dev.	0.11	0.03	0.02	0.03	0.07	0.09
	Sludge	Mean	104	39	84	38	64	26
		Std. dev.	18	28	8.14	8.32	7.68	15
Acidity	Spiked feed	Mean	460	400	400	450	450	490
	Product	Mean	13	0	0	0	0	0
Alkalinity	Spiked feed	Mean	14	17	17	15	14	14
	Product	Mean	47	36	44	50	90	1220
Aluminum	Spiked feed	Mean	13	7.7	9.0	6.6	5.4	11
	Product	Mean	0.40	0.33	0.31	0.40	0.40	0.23
Calcium	Spiked feed	Mean	360	340	340	350	340	360
	Product	Mean	470	460	480	530	610	970

(continued)

TABLE 8 (continued)

Parameter	Sample	Statistic	Nominal pH 7	8	9	10	11	12
Iron, ferrous	Spiked feed	Mean	150	160	160	150	150	150
	Product	Mean	0.25	0	0	0	0	0
Iron, total	Spiked feed	Mean	160	160	160	150	160	160
	Product	Mean	1.4	0.65	0.33	0.40	0.35	0.05
Magnesium	Spiked feed	Mean	100	100	100	98	98	100
	Product	Mean	100	96	65	25	5.0	0.06
Manganese	Spiked feed	Mean	4.8	5.4	5.3	5.0	5.0	4.8
	Product	Mean	3.7	2.5	0.19	0.06	0.06	0.05
Sodium	Spiked feed	Mean	360	350	350	340	340	360
	Product	Mean	340	340	330	340	340	340
Specific conductance	Spiked feed	Mean	2630	2460	2470	2730	2700	2620
	Product	Mean	2630	2540	2430	2840	2840	5960
Sulfate	Spiked feed	Mean	2470	2350	2350	2170	2310	2450
	Product	Mean	2400	2020	2160	2250	2340	3230
Total dissolved solids	Spiked feed	Mean	3460	3310	3310	3330	3250	3440
	Product	Mean	3310	3160	3040	3160	3290	4540

All units are mg/l except for pH and specific conductance (μmhos/cm).

REVERSE OSMOSIS

A Universal Oil Products (13) spiral-wound type reverse osmosis unit (Figure 3) with a capacity of 15 cu m/day (4,000 gpd) of product flow was studied in a one-day test. The unit operated at 35.15 kg/sq cm (500 psi) to achieve optimal rejection characteristics, at a moderate recovery rate (40 percent) to prevent fouling interferences with rejection ability, at a minimum 10:1 brine:product flow ratio to prevent boundary layer precipitation problems, and with sulfuric acid injection to control iron precipitation by maintaining an influent pH below 3. The osmotic pressure of the AMD, measured during the study, was 1.7 kg/sq cm (24 psi).

Operational parameters for the study are presented in Table 9. Although the system was on-stream for several days, all of the water samples were collected on a grab-sample basis throughout one day's operation. Four grab-samples were taken per data set (i.e., raw AMD, spiked AMD, product, and brine). Ten sets of samples (40 samples total) were collected.

A summary of chemical data is presented in Table 10. Individual data are presented in Appendix C. Since reverse osmosis product quality is not directly related to ion solubility, rejection rate or percent removal calculations are appropriate. As seen in Table 10, the rejections were below 80 percent for boron, mercury, and phosphorus and were above 90 percent for the remainder of the trace elements. The cellulose acetate membrane used in this study (Universal Oil Products Model 4T38) is characterized by high rejection rates. This is apparent with the 99.9-percent rejection observed on sodium, a monovalent ion, which is normally rejected at a 93-percent rate.

Material balances of the system are shown in Table C-6 of the Appendix and were satisfactory (within 15-percent indicated gain or loss) for all elements except mercury where 54 percent of the indicated influent failed to exit the system. It was postulated by Stuewe and Hall (14) that the mercury was precipitated upon contact with the sulfuric acid pretreatment injection and was collected on the filters in front of the reverse osmosis unit and/or on the membranes. Tests to investigate this confirmed the presence of mercury on the filters. No analyses were made on the membrane.

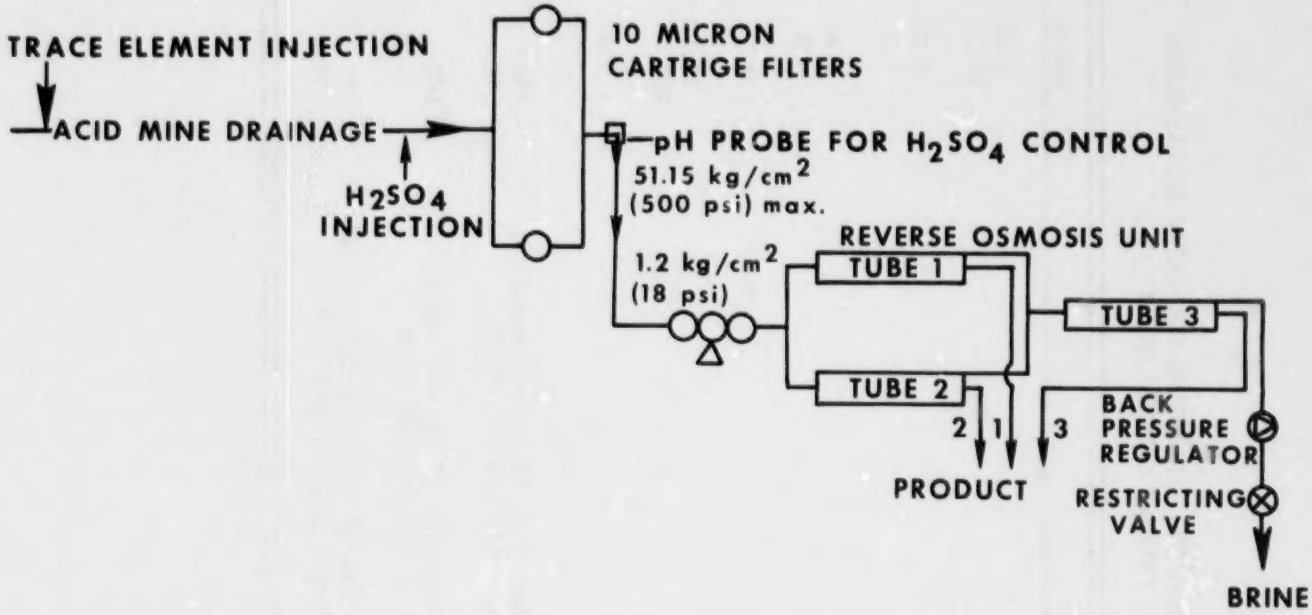


Figure 3. Flow diagram for 4000-gpd spiral-wound reverse osmosis unit.

TABLE 9. MEAN OPERATING PARAMETERS FOR CROWN SPIRAL-WOUND REVERSE OSMOSIS STUDY

Parameter	Value
AMD feed flow, liter/sec	0.65
AMD feed flow, gpm	10.3
Product flow, liter/sec	0.25
Product flow, gpm	3.9
Brine flow, liter/sec	0.40
Brine flow, gpm	6.4
Water recovery, percent	38
Feed pressure, kg/cm^2	35.50
Feed pressure, psi	505
Feed temperature, ^oC	15.5
Feed temperature, ^oF	60
Tube one flux, $liters/m^2/day$ @ 35.15 kg/cm^2 and 25^oC	616
Tube one flux, $gal/ft^2/day$ @ 500 psi and 77^oF	15.1
Tube two flux, $liters/m^2/day$ @ 35.15 kg/cm^2 and 25^oC	600
Tube two flux, $gal/ft^2/day$ @ 500 psi and 77^oF	14.7
Tube three flux, $liters/m^2/day$ @ 35.15 kg/cm^2 and 25^oC	587
Tube three flux, $gal/ft^2/day$ @ 500 psi and 77^oF	14.4

TABLE 10. REVERSE OSMOSIS WATER QUALITY SUMMARY

Parameter	Spiked feed		Product		Brine		Rejections,[a] percent
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	
Arsenic	2.29	0.14	0.01	0	3.58	0.30	99.6
Boron	2.01	0.17	0.88	0.20	3.08	0.29	56.2
Cadmium	0.83	0.06	0.006	0.009	1.22	0.13	99.3
Chromium	0.54	0.06	0.01	0	0.82	0.12	98.1
Copper	6.18	0.35	0.01	0	9.12	0.95	99.8
Mercury	0.28	0.02	0.06	0.02	0.17	0.02	78.6
Nickel	0.74	0.05	0.01	0	1.10	0.12	98.6
Phosphorus	1.50	0.35	0.32	0.13	1.93	0.42	78.7
Selenium	1.17	0.17	0.11	0.01	1.83	0.15	90.6
Zinc	6.25	0.54	0.06	0.04	9.63	1.15	99.0
pH	2.2		2.0		3.6		-
Acidity	1340		130		2070		90.3
Aluminum	5.0		0.20		7.8		96.0
Calcium	370		0.60		590		99.8
Iron, ferrous	150		<0.10		230		99.9
Iron, total	170		0.30		270		99.8
Magnesium	110		0.20		180		99.8
Manganese	5.0		0.05		7.1		99.0
Sodium	400		0.30		640		99.9
Specific conductance	5980		60		8540		99.0
Sulfate	2990		22		4610		99.3
Total dissolved solids	4040		24		6290		99.4

*All units are mg/l except for pH and specific conductance(μmhos/cm).

[a]Rejection equals $\frac{\text{feed concentration - product concentration}}{\text{feed concentration}} \times 100.$

ION EXCHANGE

A two-resin ion exchange unit (Figures 4 and 5) was studied for effectiveness of trace element removal in a one-day test. The ion exchange system, which operated at a 40-liter/min (10.5-gpm) product flow rate, was being regenerated at high dosage rates to achieve minimum cation leakage rates. The intended regeneration dosage for the cation column was 144 grams of sulfuric acid per liter of resin; for the anion column, the intended dosage was 64 grams of sodium hydroxide per liter of resin. Six grab samples (raw AMD, spiked AMD, cation effluent, anion effluent, cation regenerant, and anion regenerant) were taken per data set. While the grab sample data are indicative of system response, they do not truly represent the integrated flow from the system. The choice to take grab samples rather than composites was made because the effluent from the ion exchange system is constantly changing in quality and it was desirable to monitor trends in addition to overall effectiveness. Eight sets of grab samples were taken during the one-day study period for a total of 48 separate samples from the test. Detailed design specifications for the two-resin unit are given in Table 11. The two-resin system operated with a strong-acid cation resin that exchanged H^+ ions for the cations (arsenic, cadmium, chromium, etc.,) in the AMD. The effluent from the cation column becomes mostly sulfuric acid since the predominant anion in the AMD is sulfate. This solution of H_2SO_4 then enters the weak-base resin column where the acid is sorbed by the weak-base resin.

The actual operating parameters for the unit during the test study are presented in Table 12. These data were based on five regeneration cycles, including two cycles from which water samples were collected. The cost of regenerant chemicals alone for this study was $9.70 per 1000 gallons, illustrating that the unit was operated in the mode optimum for effluent quality and not optimum for cost/effectiveness. Regenerant utilization efficiencies for the sulfuric acid and sodium hydroxide were 22 and 42 percent respectively.

The water quality analyses for the spiked feed and cation and anion column effluents are summarized in Table 13 (individual data are in Appendix C.) The cation column was not particularly effective in arsenic, boron, or selenium removal and, interestingly, the phosphorus content in the cation effluent was significantly higher than in the influent.

The anion column (and its alkaline pH 10 conditions) very significantly reduced the residual trace element concentrations as most of the elements precipitated within the column itself at pH 10. Arsenic and boron were not removed, however, below 0.5 mg/l by the process. Additional phosphorus was added by the anion column, although not to the degree that the cation column increased phosphorus levels. Some insight into the phosphorus increase phenomenon is illustrated in Figures 6 and 7, showing the trace element trends throughout one of the two service cycles in which samples were collected. Phosphorus levels from the cation column (Figure 6) dropped sharply as the column went back on-line, indicated that the rinses following

regeneration were not long enough for effective phosphorus reduction. The unit operation could easily be modified to rinse longer and do a better job on phosphorus removal; however, the improvement would not have been worth the cost. The phosphorus phenomenon may have been analytical error; although, this is not felt to be the case because the data immediately looked suspect and the phosphorus analyses were repeated. It is more likely that the cation backwash cycle, which uses AMD, loaded the bottom of the column with phosphorus since backwash is accomplished upflow. Then the downflow regeneration was not sufficient to remove all of the phosphorus from the bottom of the cation column. When the column went back on-line, the phosphorus on the resin at the bottom of the column exchanged with cations in the AMD passing through and an increase in phosphorus was observed. Regardless of the reason, the ion exchange system was ineffective in phosphorus removal.

In terms of conventional AMD parameters, the cation column effluent dropped to pH 1.9, indicative of the exchange of H^+ ions for the cations in the raw AMD and resulting in a solution containing predominately sulfuric acid. Additional reductions of cations were observed in the anion column as insoluble hydroxides formed at the pH 10 conditions and precipitated within the resin bed. All acidity was sorbed by the weak-base resin and alkalinity and sodium increased because of excess NaOH, which was used as the regenerant. The trends of the conventional pollutants during one of the service cycles are illustrated in Figures 8 and 9.

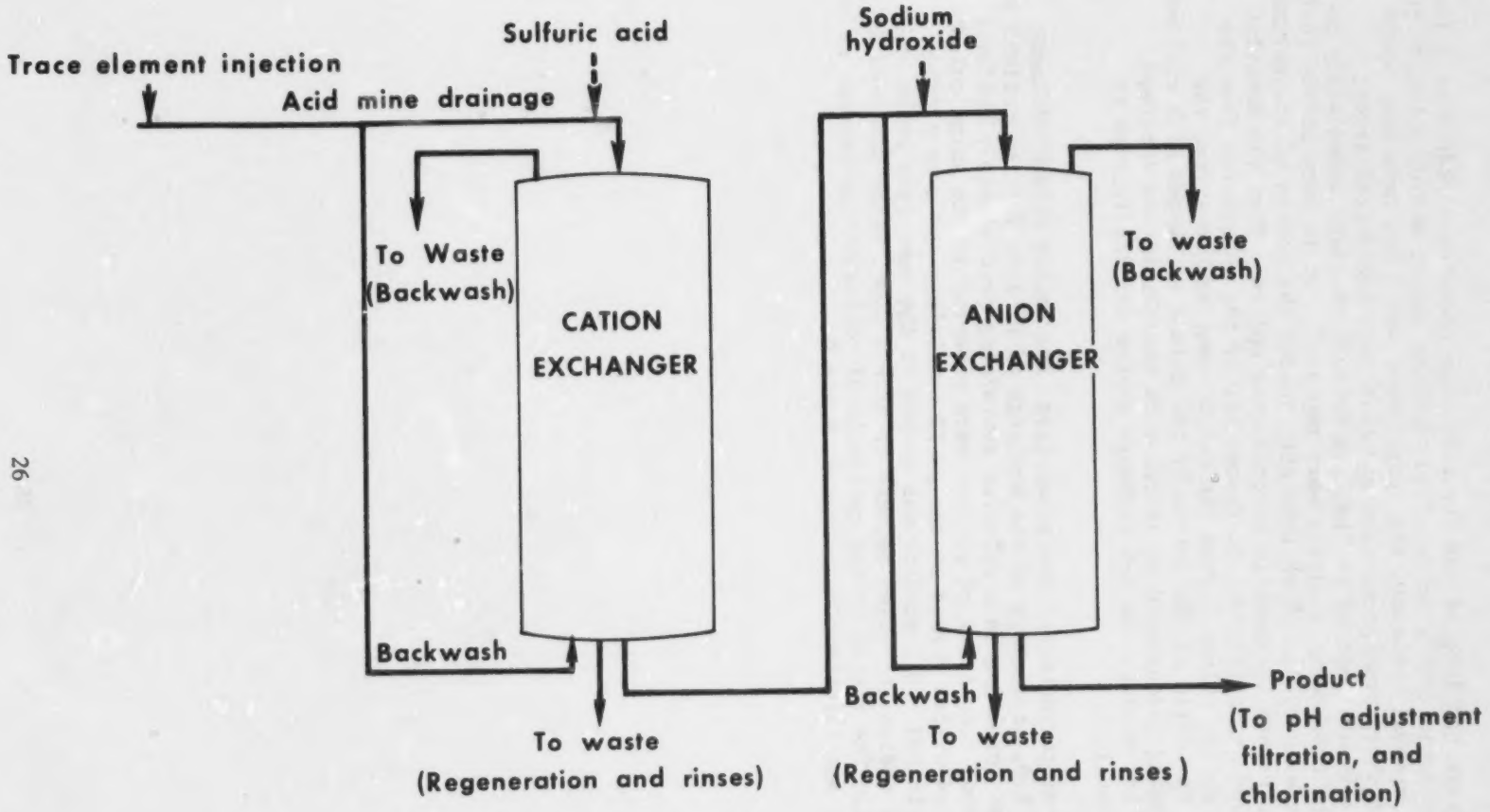


Figure 4. Schematic flow diagram of EPA 2-resin ion exchange unit.

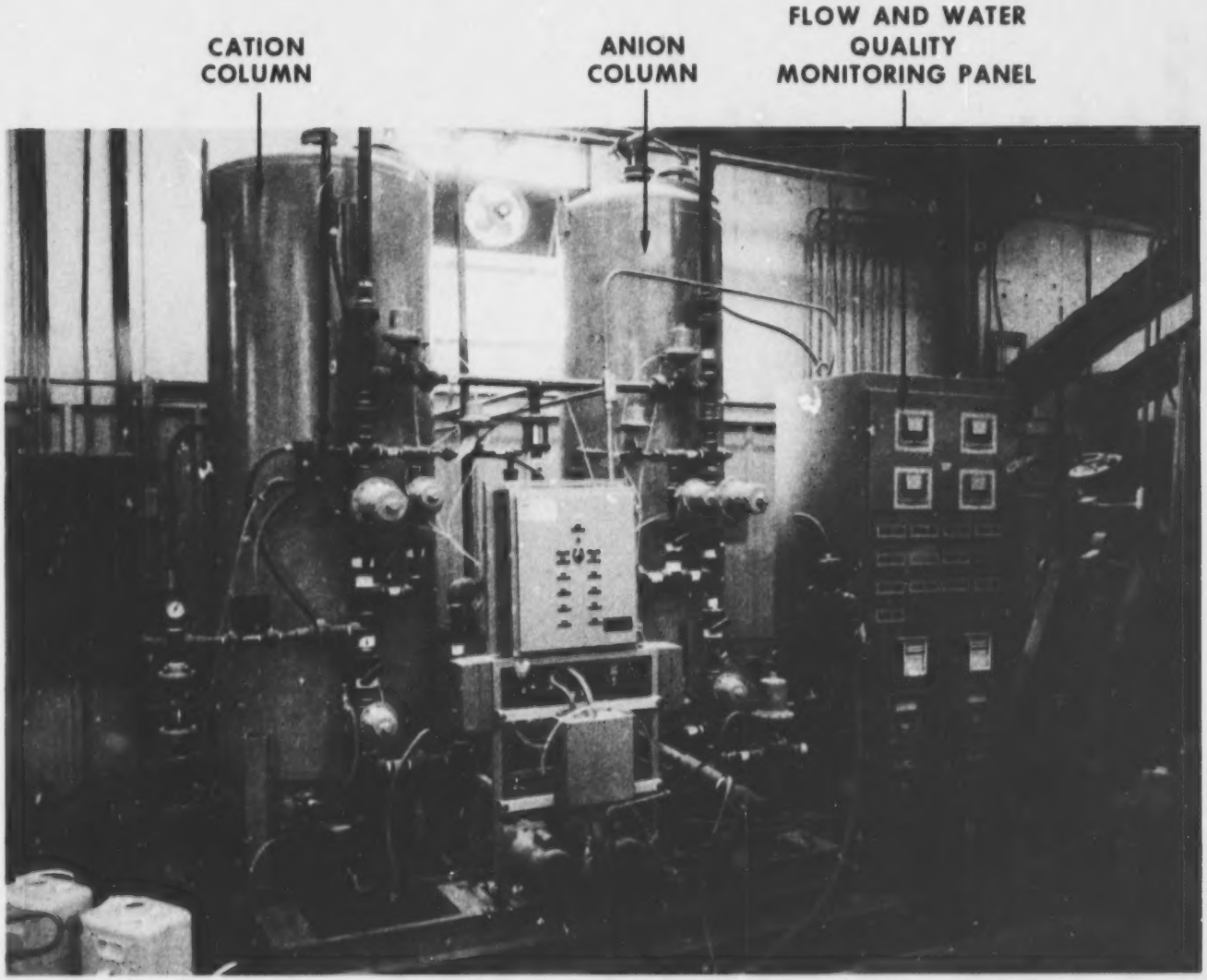


Figure 5. Photograph of the ion exchange installation at Crown.

TABLE 11. GENERAL SPECIFICATIONS FOR EPA ION EXCHANGE TREATMENT UNIT (TWO-RESIN SYSTEM)

	Cation exchanger	Anion exchanger
Type	Strong acid	Weak base
Resin	Duolite C-20	Dowex WGR
Volume of resin, cu m	0.93	0.54
Approximate tank size, cm	91 x 213	76 x 213
Approximate tank area, sq m	0.65	0.45
Service flow rate, liters/min	40	40
Service flow rate, liters/min/cu m	43	74
Service flow direction	Downflow	Downflow
Backwash flow rate, liters/min	115	100
Backwash flow rate, liters/min/sq m	180	190
Backwash flow direction	Upflow	Upflow
Bed expansion during backwash, percent	50	75
Regenerant flow rate, liters/min	100	40
Regenerant flow rate, liters/min/sq m	150	90
Regenerant flow rate, liters/min/cu m	110	74
Regenerant flow direction	Downflow	Downflow
First rinse flow rate, liters/min	100	40
First rinse flow rate, liters/min/cu m	110	90
First rinse flow direction	Downflow	Downflow
Second rinse flow rate, liters/min	115	100
Second rinse flow rate, liters/min/cu m	120	190
Second flow direction	Downflow	Downflow
Regenerant	Sulfuric acid	Sodium hydroxide
Regenerant concentration, percent by weight	2	3 to 5

TABLE 12. AVERAGE VALUES FOR THE ION EXCHANGE OPERATING PARAMETERS

Parameter	Cation	Anion
Regenerant	H_2SO_4	NaOH
Bulk regenerant cost, cents/kg	7.72	11.0*
Bulk solution concentration, weight percent	93	20
Desired regenerant concentration, weight percent	2.0	4.0
Desired dosage, grams of regenerant/liter of resin	144	64
Desired dosage, pounds of regenerant/cu ft of resin	9	4
Influent load, milligrams/liter as $CaCO_3$	2450	2650
Effluent load (leakage), milligrams/liter as $CaCO_3$	200	0
Effective removal, milligrams/liter as $CaCO_3$	2250	2650
Number of regeneration cycles during this test	5	5
Average actual dosage, grams of regenerant/liter of resin	140	61
Average actual regenerant concentration, percent by weight	2.0	3.8
Exchanger capacity, grams/liter of resin as $CaCO_3$	30.8	36.1
Exchanger capacity, kilograins/cu ft of resin as $CaCO_3$	13.4	15.8
Regenerant utilization efficiency, percent	22	42
Regenerant cost, cents/cu m	93	110
Regenerant cost, cents/1000 gal	350	420
Total volume to waste, liters/regeneration	10650	3200

*Price of 50-percent concentration and diluting on-site to 20 percent.

TABLE 13. ION EXCHANGE WATER QUALITY SUMMARY

Parameter	Spiked feed		Cation effluent		Product (anion effluent)	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
Arsenic	2.47	0.55	1.68	0.20	0.52	0.58
Boron	2.38	0.30	2.20	0.30	0.58	0.58
Cadmium	0.95	0.12	0.04	0.09	0.001	0.001
Chromium	0.63	0.08	0.05	0.02	0.01	0.01
Copper	7.27	0.86	0.11	0.05	0.03	0.03
Mercury	0.72	0.08	0.07	0.06	0.001	0.003
Nickel	0.86	0.09	0.02	0.01	0.02	0.02
Phosphorus	1.47	0.39	8.86	8.23	9.71	5.54
Selenium	1.34	0.27	1.19	0.13	0.09	0.14
Zinc	7.44	0.84	0.14	0.05	0.03	0.02
pH	4.8		1.9		9.9	
Acidity	500		2640		0	
Alkalinity	14		0		280	
Aluminum	5.7		0.20		0.19	
Calcium	350		11		8.7	
Iron, ferrous	140		2.1		0	
Iron, total	160		2.1		0.05	
Magnesium	100		2.6		2.2	
Manganese	3.9		0.09		0.05	
Sodium	380		71		330	
Specific conductance	2740		21,600		1240	
Sulfate	2400		910		580	
Total dissolved solids	3340		1000		900	

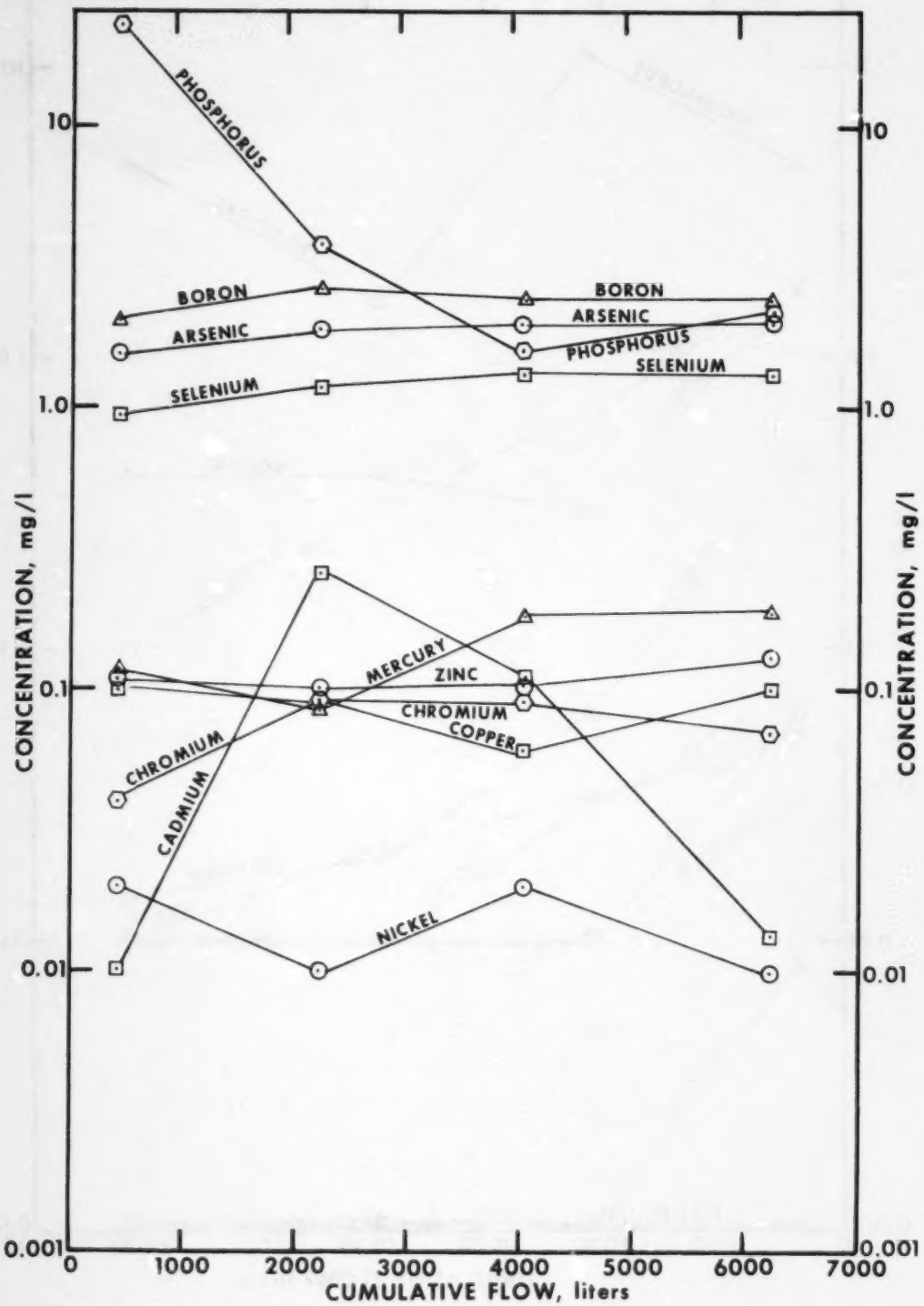


Figure 6. Trace element trends throughout the cation service cycle.

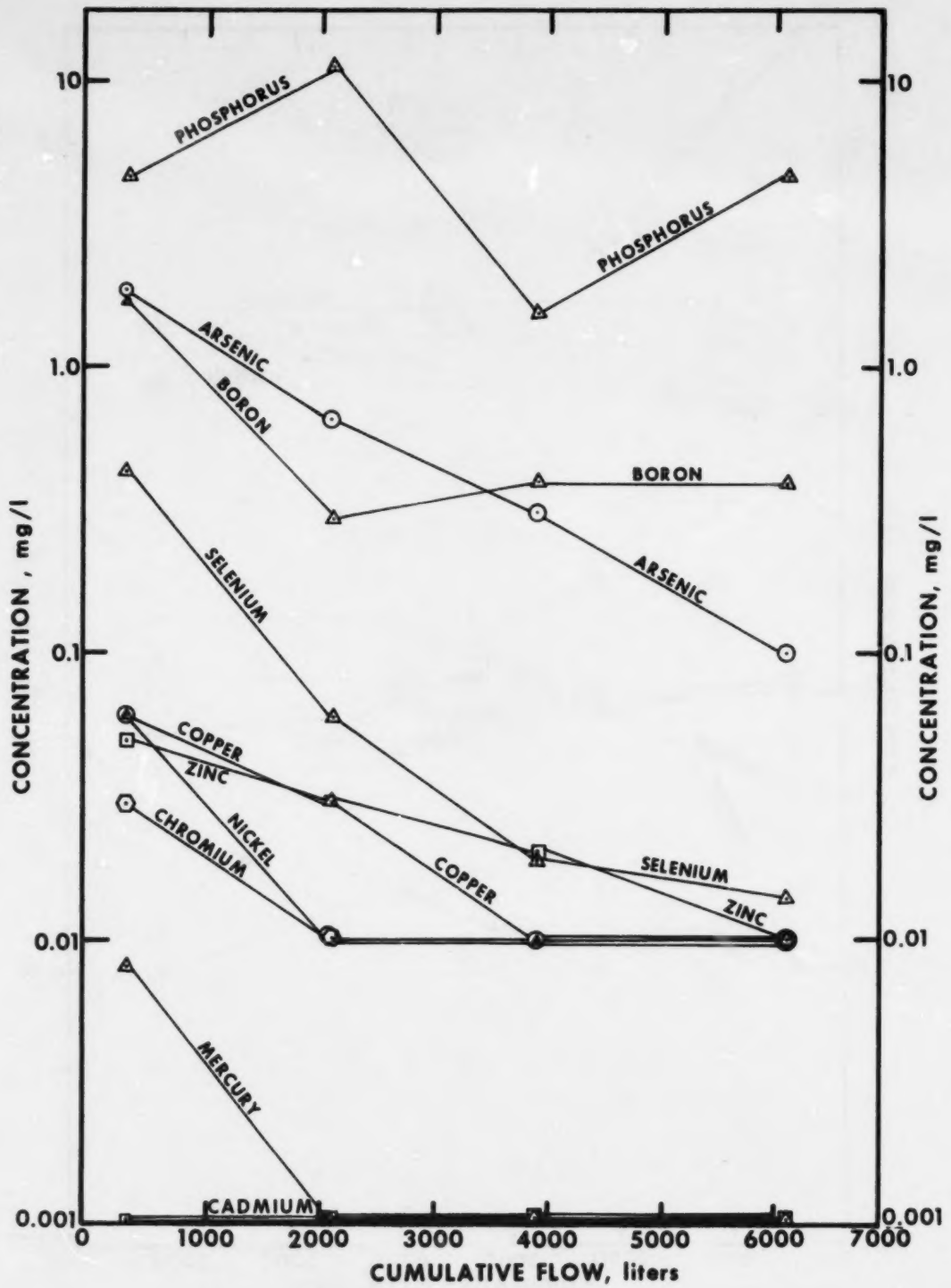


Figure 7. Trace element trends throughout the anion service cycle.

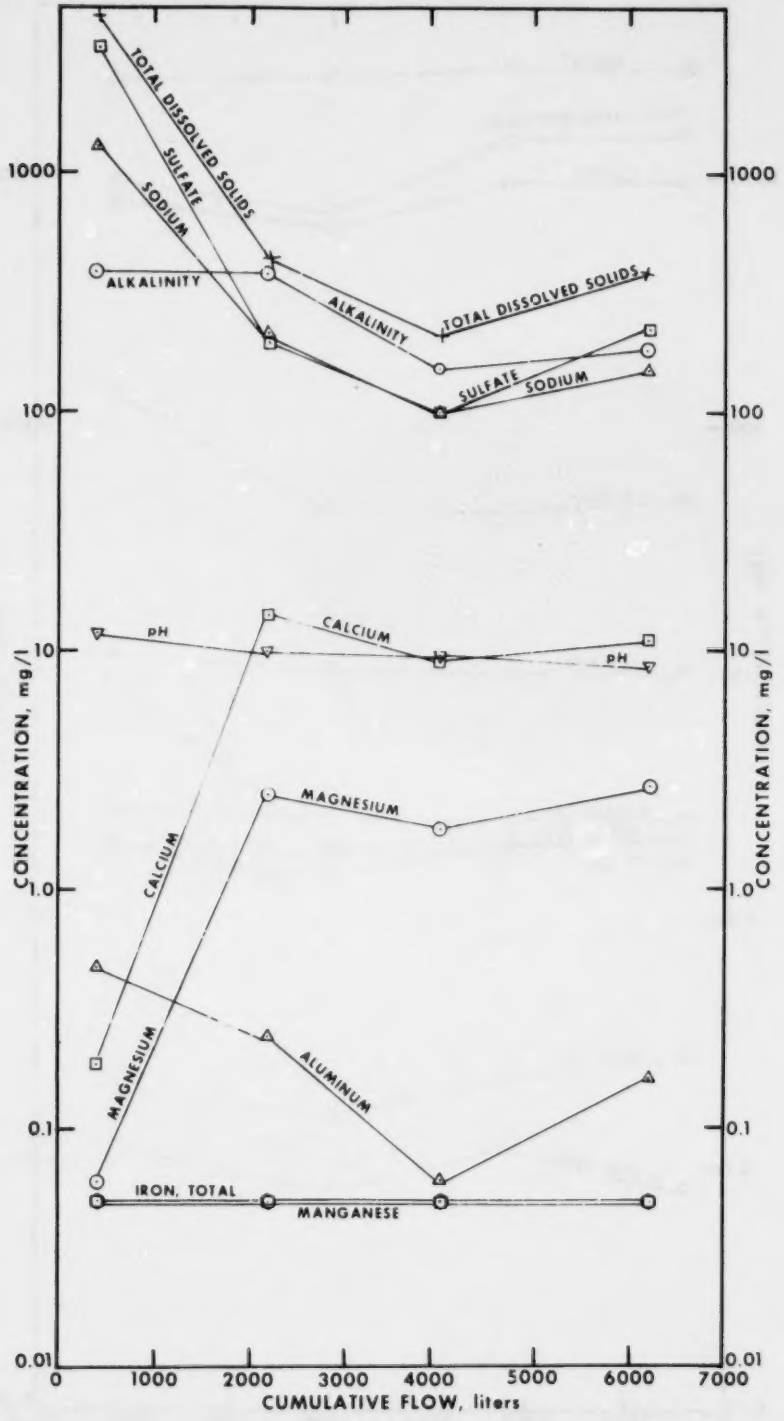


Figure 8. Conventional pollutant trends throughout the anion service cycle.

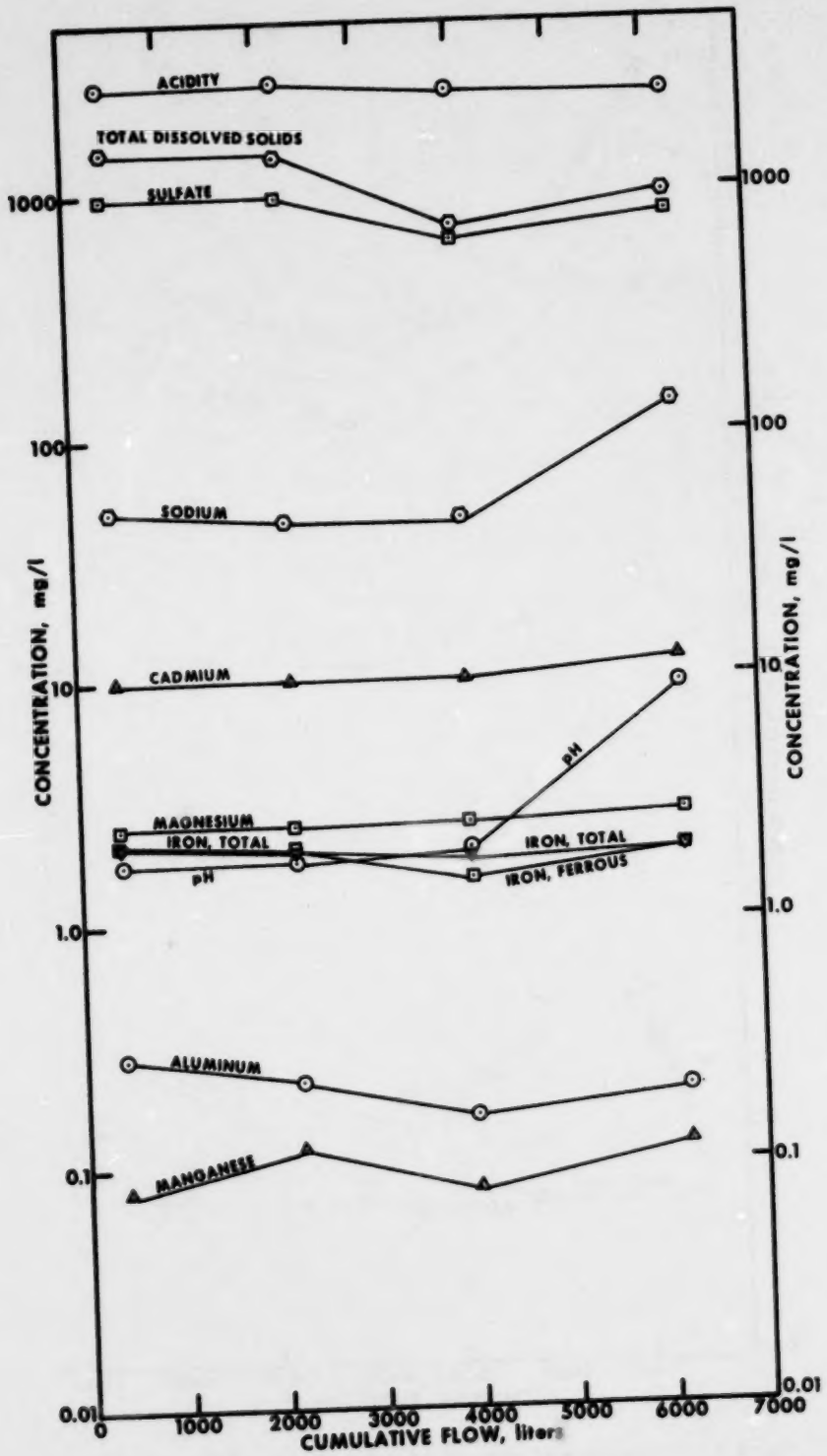


Figure 9. Conventional pollutant trends throughout the cation service cycle.

WASTE TREATMENT AND DISPOSAL

Each of the three processes studied produces a waste stream in which the pollutant concentration is significantly higher (hopefully) than in the raw AMD. Lime neutralization produces a sludge, which is very low in solids (2%) and is thus largely water. Reverse osmosis produces a low-pH brine that must be further treated with alkali neutralization and again produces a sludge similar to the lime sludge above, except for increased pollutant levels. The waste regenerants from the cation (acid) and anion (alkaline) exchange columns would be combined for partial neutralization and then fully neutralized by the addition of the appropriate alkali reagent to precipitate the metals, again producing a neutralization sludge similar to the first two. Lime would probably not be used to treat the RO and IE wastes because the increased calcium and sulfate levels would almost certainly result in heavy gypsum formation within the neutralization system. Most probably soda ash or sodium hydroxide would be used.

The effluents from the RO and IE waste neutralization would be high in TDS and calcium, and extremely high in sodium sulfate concentrations.

The presence of trace elements in the AMD source and their subsequent removal by the process and eventual concentration in a neutralization sludge adds additional concerns to the disposal of AMD sludges. Traditionally, AMD neutralization systems either return sludge to an abandoned area of a deep mine or contain it in an impoundment sized for the life of the mine. Abandonment of an impoundment after the mine ceases operation is a rarely addressed point. It is assumed that the pond would be drained, the sludge spread and air dried, and the area backfilled to cover the sludge.

The status of AMD neutralization sludge, in terms of the Resource Conservation and Recovery Act (RCRA) and the Hazardous Waste Act, is unresolved at this time. The presence of high levels of trace elements will certainly be of concern to EPA in disposal considerations.

REFERENCES

1. Wilmoth, Roger C. and James L. Kennedy. Combination Limestone-Lime Treatment of Acid Mine Drainage. Paper given at the NCA/BCR Coal Conference and EXPO III, Louisville, Kentucky. 1976.

2. Wilmoth, Roger C. Limestone and Lime Neutralization of Ferrous Iron Acid Mine Drainage. U. S. Environmental Protection Agency Report 600/2-77-101, Cincinnati, Ohio. 1977.

3. Wilmoth, Roger C. and Robert B. Scott. Water Recovery from Acid Mine Drainage. In: Proceedings 3rd National Conference Complete WateReuse, Cincinnati, Ohio. June 1976.

4. Intorre, B., et al. Treatment of Acid Mine Wastes by Ion Exchange Resins. In: Proceedings National Conference Complete WateReuse. April 1973.

5. Gulf Environmental Systems Company. Acid Mine Waste Treatment Using Reverse Osmosis. U. S. Environmental Protection Agency Report 14010 DYG 08/71, Washington, DC. 1971.

6. Wilmoth, Roger C., Donald G. Mason, and Mahendra Gupta. Treatment of Ferrous Iron Acid Mine Drainage by Reverse Osmosis. Paper given at the Fourth Symposium on Coal Mine Drainage Research, Pittsburgh, Pennsylvania. 1972.

7. Wilmoth, Roger C., Robert B. Scott, and Eugene F. Harris. Application of Ion Exchange to Acid Mine Drainage Treatment. Paper given at 32nd Annual Purdue Industrial Waste Conference, Purdue University. 1977.

8. Development Document for Interim Final and Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Ore Mining and Dressing Industry, EPA 440/1-75-061, Washington, DC. October 1975.

9. Development Document for Interim Final Effluent Limitations Guidelines and New Source Performance Standards for the Coal Mining Point Source Category, EPA 440/1-75-057 Group II, Washington, DC. October 1975.

10. Ross, Laurence W. Removal of Heavy Metals from Mine Drainage by Precipitation, EPA Report 671/2-73-080, Washington, DC. September 1973.

11. Miller, Jan D. Removal of Dissolved Contaminants from Mine Drainage, EPA-R2-72-130, Washington, DC. December, 1972.

12. Methods for Chemical Analysis of Water and Wastes. EPA 625/16-74-003. Cincinnati, Ohio. 1974.

13. Wilmoth, Roger C. Applications of Reverse Osmosis to Acid Mine Drainage Treatment. U. S. Environmental Protection Agency Report 670/2-73-100, Cincinnati, Ohio. 1973.

14. Stuewe, C. and J. Hall, personal communication. November 1977.

15. Feldman, Cyrus. Evaporation of Boron from Acid Solutions and Residues. Anal. Chem. 33:1916-1920. 1961.

16. Handbook for Analytical Quality Control in Water and Wastewater Laboratories. U. S. EPA, Analytical Quality Control Laboratory, Cincinnati, Ohio. 1972.

APPENDIX A

DISCUSSION OF ANALYTICAL RESULTS

This section (1) reviews in detail the analytical problems encountered during the study, (2) gives an analytical interpretation of the significance and trends of the data, and (3) reviews the quality assurance program and present examples of the reporting format and QA results developed by Stewart Laboratories.

PROBLEMS ENCOUNTERED

In the initial stages of developing the program for preserving and shipping the samples from the EPA Crown site to Knoxville, Tennessee, Hydroscience and their analytical subcontractor, Stewart Laboratories, reviewed the EPA methods manual (12) for the proper preservation procedures. The manual listed two techniques which were felt to cover the compounds in this study. One preservation procedure was for metals and required acidification with 1-1 nitric acid; the other procedure was for phosphorus which required acidification with sulfuric acid. Since nitric acid is used in the digestion for total phosphorus analysis, it was recommended that duplicate samples, including a different preservative for each, were unnecessary and samples preserved with nitric would be satisfactory. This procedure was reviewed with the EPA personnel during start-up, and then the sampling program began. When the analytical program was begun by Stewart, it soon became evident that nitrates were interfering in the boron methodology by giving erratic and odd results. This problem occurred essentially for the following reasons:

1. Lack of experience within Hydroscience, Stewart Laboratories, and the EPA in analyzing for boron.

2. The EPA manual did not have a preservation technique for boron or a warning in the metals section not to preserve samples requiring boron analysis by nitric acid addition. The new edition of the manual will have such a warning.

The solution of the problem was first to stop the boron analysis on the preserved samples, send small unpreserved samples for subsequent boron analysis (started on 10/5/77), and then look at alternate analytical techniques to detect boron in the presence of large concentrations of nitrates. The first alternate analytical technique tried was a modification of the Feldman method (15). This method requires the addition of mannitol to the sample, reduction to a residue, and analysis by an emission spectrographic method using a powder d-c arc technique. This method gave an extremely hygroscopic residue which was impossible to weigh accurately. A USGS technique was tested that

called for a sulfuric acid addition to the sample followed by volume reduction to a residue at temperatures less than 225°C. Stewart attempted the technique several times on standards, samples and spiked samples, but did not get acceptable results.

Since significant time had been expended unsuccessfully in an effort to find an alternative technique, and funds for further such work were not available in this task, all attempts to find a way of analyzing the preserved samples for boron were stopped.

Later during the task, alledgedly unpreserved samples from the early lime neutralization runs were found at the EPA Crown site. They were sent to Hydroscience for boron analysis. During a quick screening for nitrates prior to analysis, it was found that the only good samples were those taken during the period from September 21, 1977 and September 23, 1977. This, however, was helpful in filling some of the boron data gaps.

A similar problem also occurred with the sludge samples. They were not preserved, but the EPA digestion procedure for metals calls for a nitric-sulfuric acid digestion. A separate sulfuric acid digestion for boron only was incorporated into the procedure. At about the same time, it was realized that Stewart Laboratories was decanting the sludge samples for analysis of the "sludge" portion only; therefore, the retainer samples were requested and the analyses were repeated using the total sample and the modified digestion procedure mentioned above.

ANALYTICAL INTERPRETATION

Since this report consists of a great deal of analytical data for metals at the ppm and ppb levels, it is worthwhile to review the meaning of the data and its interpretation based on detection limits of the analytical methods utilized and the precision and accuracy data developed in the QA program. It is also important to review the types of data anomalies that occasionally occurred.

Three significant figures were realistically reported for all elements except mercury and boron. The analytical method and our studies showed a reproducible detection limit for mercury to be 0.0002 mg/liter; therefore, in some places, four significant figures were reported. In the case of boron, only two significant figures were reported, since the detection limit is 0.1 mg/liter. For the purposes of data summaries as appear in the text, these were generally rounded to two decimal places.

Throughout the study replicate samples were analyzed as blind splits, and occasionally the difference encountered in these "duplicates" was greater than expected from the precision and accuracy data. This variation has been attributed to the inability of the analyst to obtain a proper sample for analysis or to an error in making a proper "true" split.

An unexpected result of this study was that the accuracy and precision data for the sludge samples (containing fine settleable solids) were equal to or better than the feed and product water samples for all the metals in the study.

In reviewing the analytical results from the reverse osmosis unit run, it was found that mercury in the spiked AMD was consistently lower than expected (by approximately one-half), which was first thought to be an analytical error. In reviewing the data and performing additional analysis, the analysis was eliminated as the problem source. A definite answer was not found for the data anomalies, but could have been due to a process phenomena (e.g., addition of sulfuric acid with subsequent precipitation of mercuric sulfate, which could have been removed by an RO prefilter prior to sampling the spiked AMD feed).

REVIEW OF QUALITY ASSURANCE PROGRAM

The essential and important part of this quality assurance program was to provide quality control checks on the instrumentation, personnel, and analytical procedures. Hydroscience and Stewart Laboratories used the EPA Handbook for Analytical Quality Control in Water and Wastewater (16) as the minimum standard quality control reference. The overall program consisted of the Stewart Laboratories program outlined below, along with frequent reviews by Hydroscience and submission of blank and spiked standards during the course of the study.

The Analytical Quality Control Program of Stewart Laboratories, Inc. (SLI) consisted of four separate areas integrated into the total effort; namely, the intralaboratory quality control program, interlaboratory studies, collaborative testing projects, and external quality control programs imposed and administered by Hydroscience.

INTRALABORATORY QUALITY CONTROL PROGRAM

The attainment and maintenance of the program was the direct responsibility of the SLI laboratory director. This phase of the program was divided into two segments--a routine program applicable to all test procedures and custom internal QA programs designed for individual contract efforts.

Routine Program

The quality control procedures associated with the routine intralaboratory program, which are applicable to all test procedures, were also applied to the project. This included such items as:

a. Deionized water was continuously monitored by a conductance method to assure that ASTM Type II grade reagent water was used for all analytical procedures.

b. Reference standards were NBS or certified to meet NBS standards.

c. Wavelength standard curves and standard cells for spectrophotometers were checked during the project.

d. Analytical balances were checked against reference weights (NBS Class S) on a one-a-month schedule.

e. All laboratory reagents met ACS standards and were labeled contents, date of preparation, and expiration when applicable.

f. Volumetric glassware was NBS Class A.

g. Glassware was checked for cleanliness and for detergent removal prior to each analysis run.

Custom Internal Quality Control Programs

In addition to the general program, custom internal quality control programs are designed for individual contract efforts. For purposes of this project, the internal QA program included blind splits of actual samples (replicate analyses); blind random analysis of standard reference materials; and recovery studies with spiked samples to establish method precision and accuracy. One sample from each analysis lot or 15% of the samples in an analysis lot were run as blind splits. During the course of the project, replicates and spikes were done on all types of samples (17 types - 7 replicates of each one). Reference standards obtained from Environmental Resource Associates were analyzed along with the samples.

Representative sample bottles from the cleaning and preparation operation were selected by Hydroscience and filled with previously tested "blank" water. These blank control samples were analyzed by the appropriate techniques before the final shipment of the containers to the field and were found to be free of possible contamination or interferences.

During the course of the project, the following types of data were produced to check the QA program and determine the necessary statistics to evaluate the data:

a. Daily standard curves.

b. Precision data on all parameters in all different types of samples.

c. Accuracy data on all parameters in all different types of samples.

d. Blind replicates.

e. Blind spikes.

f. Quality control charts.

g. Blind quality control samples.

All of the above were reported in the five weekly reports, and examples of each follow:

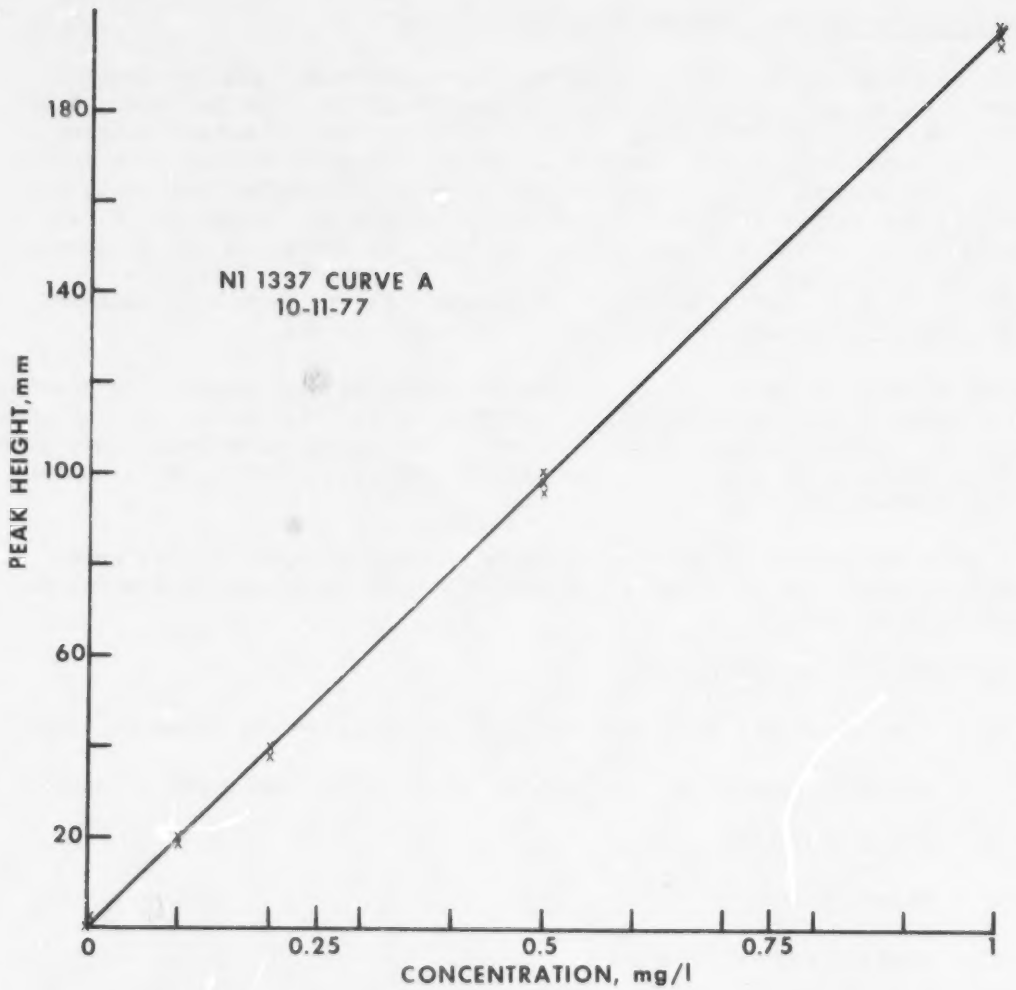


Figure A-1. Example of daily standard curve.

TABLE A-1. EXAMPLE OF PRECISION DATA
(Water Sample Analyses for Mercury)
(mg/1)

Sample	AMD (10-6-77) Time: 15:00	AMD-A (10-5-77) Time: 8:30	AMD product A (10-5-77) Time: 8:30
1	<0.0002	0.494	0.019
2	<0.0002	0.519	0.020
3	<0.0002	0.489	0.019
4	<0.0002	0.484	0.019
5	<0.0002	0.494	0.019
6	<0.0002	0.494	0.019
7	<0.0002	0.494	0.019
Average	<0.0002	0.495	0.019
Std.dev.	0	0.0111	0.0004
Coef. of variation	0	2.24	2.11

TABLE A-2. EXAMPLE OF ACCURACY DATA FOR PHOSPHORUS
(mg/l for water, µg/g for sludge)

Sample	Source and spiking level			
	AMD (10/8/77-1500) Added 2.5 mg P/1	AMD-A (10/8/77-1500) Added 2.5 mg P/1	Product A (10/8/77-1500) Added 2.5 mg P/1	Sludge A (10/5/77--830) Added 25.0 µg/g
1	9.58	10.5	4.74	71.5
2	9.06	9.68	4.72	74.0
3	10.7	9.23	5.00	75.0
4	9.84	10.2	4.80	76.4
5	8.06	10.0	5.02	79.3
6	10.1	9.15	5.78	73.0
7	7.96	10.7	5.56	73.0
Average	9.33	9.92	5.09	74.6
Percent recovery	$\frac{9.33}{6.84+2.50} = 99.9$	$\frac{9.92}{7.66+2.50} = 97.6$	$\frac{5.09}{2.80+2.50} 96.0$	$\frac{74.6}{49.0+25} = 101$

Stewart Laboratories, Inc.

5815 MIDDLEBROOK PIKE KNOXVILLE, TENNESSEE 37921

CERTIFICATE OF ANALYSIS

TO: Mr. Jack Hall
Hydroscience, Inc.
9041 Executive Park Drive
Knoxville, TN 37919

DATE REPORTED: October 12, 1977
CODE:
ORDER No.:

Sample Description: AMD - B (10-1-77) 1500

Concentration units are mg/liter (ppm)

	Original Analysis	Blind Split
Arsenic	2.00	2.05
Cadmium	0.777	0.800
Chromium	0.72	0.69
Copper	6.49	6.22
Mercury	0.484	0.479
Nickel	0.80	0.78
Selenium	1.18	1.21
Zinc	6.57	6.51
Phosphorus	3.90	3.20

Sworn to and subscribed before me this 12th
day of October 1977

Peggy W. Thigpen
NOTARY PUBLIC

My commission expires December 23, 1979

STEWART LABORATORIES, INC.

By

Figure A-2. Example of blind split analysis certification.

Stewart Laboratories, Inc.

5815 MIDDLEBROOK PIKE KNOXVILLE, TENNESSEE 37921

CERTIFICATE OF ANALYSIS

TO: Mr. Jack Hall
Hydroscience, Inc.
9041 Executive Park Drive
Knoxville, TN 37919

DATE REPORTED: October 12, 1977
CODE:
ORDER No.:

Sample Description: AMD-B (10-6-77) Time: 0830

Concentration units are mg/liter (ppm)

	Sample No. 7324	7324 + Spike	Conc. Spike	Recovery (%)
Arsenic	2.08	3.95	2.00	96.8
Cadmium	0.511	1.20	0.75	95.2
Chromium	0.37	0.91	0.50	105.
Copper	4.27	8.18	4.00	98.9
Mercury	0.499	1.10	0.500	110.
Nickel	0.54	1.25	0.80	93.3
Selenium	0.980	2.05	1.00	104.
Zinc	4.45	8.50	4.00	101.
Phosphorus	7.15	8.90	2.50	92.2

Sworn to and subscribed before me this 12th day of October 1977

Peggy M. Thigpen
NOTARY PUBLIC

My commission expires December 23, 1979

STEWART LABORATORIES, INC.

By Anna M. Graham

Figure A-3. Example of spiked sample analysis certification.

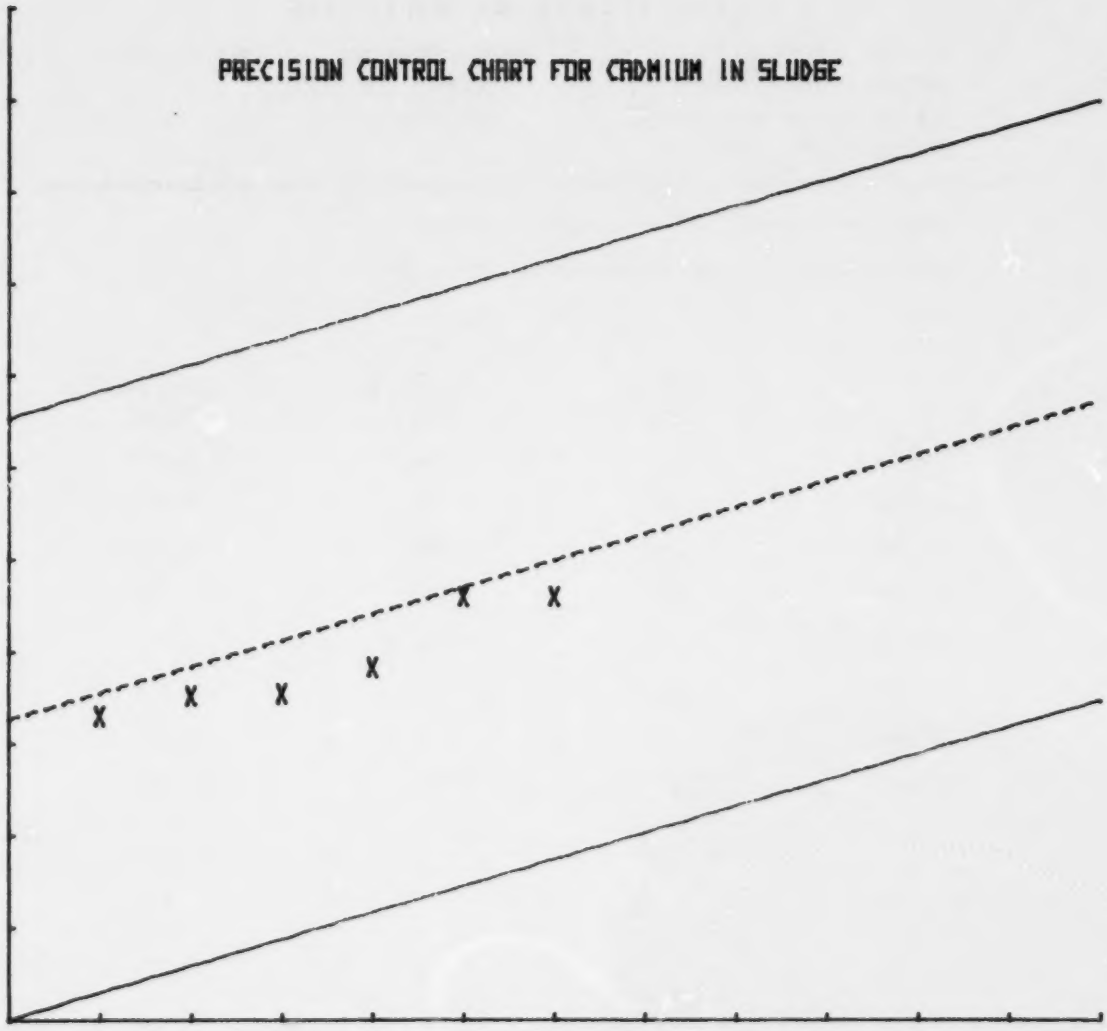


Figure A-4. Example of precision control chart.

Stewart Laboratories, Inc.

5815 MIDDLEBROOK PIKE KNOXVILLE, TENNESSEE 37921

CERTIFICATE OF ANALYSIS

TO: Mr. Jack Hall
Hydroscience, Inc.
9041 Executive Park Drive
Knoxville, TN 37919

DATE REPORTED: October 19, 1977
CODE:
ORDER No.:

Sample Description: QC Sample (ERA Lot #1762)

Concentration units are micrograms per liter (ppb)

	Analysis Result	Certified Value	Acceptable Range
Arsenic	110.	110.	100-120.
Cadmium	75.	83.	79-87.
Chromium	350.	350.	330-370.
Copper	280.	275.	265-285.
Mercury	4.3	4.4	4.2-4.6
Nickel	440.	440.	425-455.
Selenium	73.	67.	61-73.
Zinc	310.	310.	295-325.

Sworn to and subscribed before me this 19th
day of October 1977

NOTARY PUBLIC

My commission expires December 23, 1979

STEWART LABORATORIES, INC.

By

Figure A-5. Example of blind standard analysis certification.

APPENDIX B

OUTLINE OF ANALYTICAL METHODS AND INSTRUMENTATION

The analytical methods used in this project were essentially those described in the EPA methods manual (10) and listed in Table B-1. These methods and the instrumentation employed are briefly reviewed below:

SAMPLE DIGESTION PROCEDURE

There were three acid digestion procedures used (1) Boron - 50 ml of sample was digested with 1:1 sulfuric acid; (2) Phosphorus - 50 ml of sample was digested with 1 ml concentrated sulfuric acid and 5 ml of concentrated nitric acid; and (3) Metals - the complete procedure outlined in the EPA manual (10) on page 82, section 4.1.3 was followed.

ATOMIC ABSORPTION PROCEDURE - GENERAL

The parameters including cadmium, chromium, copper, nickel, and zinc were analyzed on an Instrumentation Laboratory (IL) Model 151 AA/Emission Spectrometer with automatic simultaneous background correction and recorder output. An air-acetylene flame with appropriate hollow cathode tubes at the proper wavelength was used in all cases.

ATOMIC ABSORPTION PROCEDURE - HYDRIDE

In the determination of arsenic and selenium in all samples, an Instrumentation Laboratory gaseous hydride generator was used. The gaseous hydride is swept into an argon-hydrogen flame of an IL Model 453 AA/Emission Spectrometer with dual double-beam reference optics and automatic simultaneous background correction and response recorded at 193.7 mm for arsenic and 196.0 mm for selenium.

ATOMIC ABSORPTION - COLD VAPOR

The IL Model 453 AA equipped with an IL Model 455 Flameless Atomizer was used for the mercury analysis. The method involves the reduction of mercury to the elemental state and aeration from solution into a closed cell where the absorption of radiation at 253.7 mm by the mercury vapor is recorded.

BORON - COLORIMETRIC

The unpreserved sample or sample digested with sulfuric acid was passed through a column of acidic cation-exchange resin. This solution was evaporated in the presence of curcumin forming a red product, rosocyanine. The residue was the dissolved in ethanol and read on a Beckman Model DU Spectrophotometer at 540 mm.

TOTAL PHOSPHORUS - COLORIMETRIC

Following persulfate digestion, all phosphorus converted to ortho-phosphorus was reacted in an acid medium with ammonium molybdate and antimony potassium tartrate. This complex was then reduced to a blue-colored complex by ascorbic acid and the color measured on a Beckman DU Spectrophotometer at 650 mm.

TABLE B-1. APPLICABLE ANALYTICAL METHODOLOGY

Parameter	Detection Limit µg/l	Method
As, inorganic	10	AA (hydride)
B	100	Colorimetric
Cd	2	AA
Cr	20	AA
Cu	10	AA
Pb	50	AA
Hg	0.2	AA (cold vapor)
Ni	20	AA
Se	2	AA (hydride)
Zn	5	AA
Total P	10	Colorimetric

TABLE C-1. TRACE ELEMENT POLLUTANT ANALYSES FOR LIME NEUTRALIZATION
(mg/l for water, µg/g for sludge)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
					pH 11 (Process A) vs pH 10 (Process B)							
9-21-77	0830	AMD	0.01	0.4	<0.001	0.05	0.01	0.0003	0.17	<0.001	0.260	32.4
9-21-77	0830	AMD-A	1.85	2.3	1.28	0.60	6.36	0.644	0.69	0.974	6.45	35.5
9-21-77	0830	AMD-B	1.24	2.8	0.960	0.48	4.32	0.474	0.57	0.866	5.04	34.0
9-21-77	0830	Product A	0.04	2.3	0.020	0.06	0.10	0.032	0.05	0.339	0.159	7.85
9-21-77	0830	Product B	0.03	1.7	0.013	0.06	0.07	0.014	0.05	0.315	0.130	5.95
9-21-77	0830	Sludge A	23.8	5.0	15.8	4.88	61.4	3.84	7.30	5.90	69.0	34.0
9-21-77	0830	Sludge B	10.4	1.4	9.18	2.68	30.4	1.81	3.64	3.06	35.8	20.0
9-21-77	1500	AMD	0.01	0.5	<0.001	0.05	0.03	0.0002	0.21	<0.001	0.268	33.5
9-21-77	1500	AMD-A	1.98	2.2	1.41	0.63	6.19	0.692	0.78	1.03	7.10	33.5
9-21-77	1500	AMD-B	1.58	2.6	1.03	0.46	4.40	0.484	0.64	0.877	5.41	34.5
9-21-77	1500	Product A	0.03	1.8	<0.001	0.05	0.03	0.021	0.06	0.337	0.006	2.80
9-21-77	1500	Product B	0.03	1.7	0.002	0.05	0.03	0.007	0.05	0.245	0.004	3.80
9-21-77	1500	Sludge A	23.8	6.3	15.8	4.80	60.0	4.02	7.20	5.06	71.0	34.6
9-21-77	1500	Sludge B	13.8	2.1	9.96	3.20	35.2	2.24	4.46	2.90	43.8	22.2
9-22-77	0830	AMD	0.02	*	<0.001	0.04	0.01	0.0002	0.19	<0.001	0.320	41.0
9-22-77	0830	AMD-A	2.08	*	1.36	0.56	6.11	0.556	0.82	1.19	6.91	42.0
9-22-77	0830	AMD-B	1.87	*	1.08	0.43	4.72	0.470	0.65	0.768	5.46	40.5
9-22-77	0830	Product A	0.03	*	0.020	0.06	0.09	0.029	0.06	0.422	0.108	4.90
9-22-77	0830	Product B	0.02	*	0.012	0.08	0.06	0.010	0.08	0.265	0.062	4.35
9-22-77	0830	Sludge A	26.2	4.1	15.8	4.98	62.6	4.58	7.73	4.56	73.0	34.6
9-22-77	0830	Sludge B	11.1	2.9	7.34	2.42	22.8	1.38	3.14	2.50	30.8	16.2
9-22-77	1500	AMD	0.01	*	<0.001	0.06	0.02	<0.0002	0.16	0.001	0.295	3.15
9-22-77	1500	AMD-A	2.45	*	1.31	0.62	6.23	0.580	0.72	1.24	6.50	5.00
9-22-77	1500	AMD-B	1.91	*	1.05	0.47	4.82	0.468	0.60	0.818	5.10	4.80
9-22-77	1500	Product A	0.03	*	0.019	0.06	0.07	0.018	0.07	0.372	0.088	1.50
9-22-77	1500	Product B	0.02	*	0.014	0.05	0.06	0.007	0.05	0.206	0.073	1.90
9-22-77	1500	Sludge A	22.8	9.1	15.3	4.16	52.6	3.46	7.10	4.48	64.0	25.0
9-22-77	1500	Sludge B	14.4	0.75	10.2	3.12	32.8	2.24	4.63	3.42	39.8	18.0

TABLE C-1 (Continued)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
9-23-77	0800	AMD	0.01	0.3	<0.001	0.04	0.02	<0.0002	0.17	<0.001	0.293	3.90
9-23-77	0800	AMD-A	2.17	1.9	1.31	0.75	6.28	0.600	0.75	1.04	6.72	5.20
9-23-77	0800	AMD-B	1.78	2.5	1.01	0.69	4.87	0.464	0.61	0.715	5.26	5.55
9-23-77	0800	Product A	0.01	1.7	0.004	0.04	0.03	0.010	0.04	0.368	0.084	2.60
9-23-77	0800	Product B	0.01	1.8	0.003	0.06	0.03	0.005	0.07	0.261	0.049	1.90
9-23-77	0800	Sludge A	23.6	1.3	15.3	4.88	56.4	3.93	7.70	5.04	65.0	56.0
9-23-77	0800	Sludge B	13.6	0.3	6.82	3.02	32.8	1.96	4.36	3.08	39.8	18.0
9-23-77	1500	AMD	0.01	0.7	<0.001	0.04	0.02	0.0004	0.15	<0.001	0.249	4.10
9-23-77	1500	AMD-A	2.21	1.9	1.22	0.65	5.77	0.546	0.69	1.01	6.12	5.00
9-23-77	1500	AMD-B	1.89	2.3	0.938	0.56	4.75	0.429	0.62	0.798	5.20	4.80
9-23-77	1500	Product A	0.03	1.8	0.013	0.05	0.07	0.012	0.06	0.432	0.100	3.30
9-23-77	1500	Product B	0.02	1.5	0.010	0.06	0.06	0.009	0.06	0.257	0.075	1.65
9-23-77	1500	Sludge A	16.5	9.6	13.5	3.64	46.4	3.04	6.26	4.36	53.8	34.2
9-23-77	1500	Sludge B	13.1	3.8	10.7	3.54	40.2	2.81	5.72	3.84	47.8	22.0
9-24-77	0800	AMD	0.01	*	<0.001	0.04	0.02	<0.0002	0.16	0.002	0.525	4.95
9-24-77	0800	AMD-A	2.10	*	1.24	0.71	6.20	0.595	0.75	0.970	6.44	6.50
9-24-77	0800	AMD-B	1.78	*	1.07	0.55	5.10	0.459	0.64	0.767	5.42	4.20
9-24-77	0800	Product A	0.02	*	0.011	0.04	0.06	0.018	0.05	0.448	0.098	3.65
9-24-77	0800	Product B	0.02	*	0.012	0.04	0.05	0.009	0.06	0.344	0.075	1.40
9-24-77	0800	Sludge A	19.2	4.3	11.8	3.82	45.2	4.21	6.06	3.92	51.8	21.0
9-24-77	0800	Sludge B	7.30	2.1	4.44	1.56	16.7	1.29	2.50	2.16	21.6	11.0
9-24-77	1500	AMD	0.01	*	<0.001	0.03	0.02	<0.0002	0.17	0.002	0.293	6.50
9-24-77	1500	AMD-A	2.07	*	1.29	0.64	6.05	0.566	0.74	0.990	6.33	4.95
9-24-77	1500	AMD-B	1.96	*	1.10	0.58	5.40	0.507	0.67	0.798	5.69	4.95
9-24-77	1500	Product A	0.03	*	0.008	0.04	0.05	0.018	0.05	0.396	0.262	1.85
9-24-77	1500	Product B	0.02	*	0.009	0.04	0.05	0.007	0.06	0.320	0.063	2.05
9-24-77	1500	Sludge A	26.6	3.8	13.5	4.80	60.0	4.12	7.22	5.00	66.0	32.0
9-24-77	1500	Sludge B	17.5	2.0	9.18	3.20	37.8	2.52	4.80	2.74	42.8	22.0

(continued)

TABLE C-1 (Continued)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
					pH 9 (Process A) vs pH 8 (Process B)							
9-28-77	0800	AMD	0.01	*	<0.001	0.03	0.02	<0.0002	0.16	<0.001	0.311	3.35
9-28-77	0800	AMD-A	1.87	*	0.950	0.54	4.71	0.361	0.59	0.590	4.94	5.05
9-28-77	0800	AMD-B	2.05	*	1.04	0.59	5.05	0.449	0.61	0.869	5.31	5.75
9-28-77	0800	Product A	0.03	*	0.019	0.04	0.09	0.007	0.07	0.158	0.108	1.85
9-28-77	0800	Product B	0.05	*	0.071	0.04	0.14	0.012	0.21	0.095	0.210	1.25
9-28-77	0800	Sludge A	26.6	3.0	15.8	5.42	63.8	4.49	8.26	8.30	76.0	36.2
9-28-77	0800	Sludge B	11.9	3.9	6.56	2.34	25.4	1.81	3.04	3.50	31.8	12.2
9-28-77	1500	AMD	0.01	*	<0.001	0.04	0.02	<0.0002	0.17	<0.001	0.264	11.1
9-28-77	1500	AMD-A	1.82	*	1.05	0.52	5.10	0.449	0.65	0.818	5.20	11.5
9-28-77	1500	AMD-B	1.69	*	0.990	0.51	4.90	0.444	0.62	0.900	5.20	11.6
9-28-77	1500	Product A	0.04	*	0.019	0.03	0.10	0.008	0.06	0.149	0.110	4.70
9-28-77	1500	Product B	0.06	*	0.074	0.03	0.16	0.012	0.20	0.066	0.206	4.40
9-28-77	1500	Sludge A	27.2	3.0	19.1	6.34	81.4	5.60	10.2	9.60	93.4	46.2
9-28-77	1500	Sludge B	9.60	3.0	6.56	2.24	24.2	1.86	2.60	3.68	30.8	14.0
9-29-77	0830	AMD	0.02	*	<0.001	0.03	0.01	<0.0002	0.21	<0.001	0.358	6.20
9-29-77	0830	AMD-A	1.76	*	1.02	0.53	5.00	0.322	0.69	0.950	5.47	7.50
9-29-77	0830	AMD-B	1.78	*	1.02	0.52	5.00	0.356	0.71	0.940	5.36	7.15
9-29-77	0830	Product A	0.03	*	0.482	0.05	0.10	0.006	0.05	0.162	0.098	2.05
9-29-77	0830	Product B	0.04	*	0.070	0.04	0.14	0.011	0.05	0.059	0.191	3.40
9-29-77	0830	Sludge A	27.8	2.4	16.1	5.42	67.6	4.67	9.40	8.22	78.0	49.6
9-29-77	0830	Sludge B	37.0	1.8	22.8	7.08	90.0	6.70	10.3	8.30	107.	27.4
9-29-77	1400	AMD	0.02	*	0.002	0.10	0.04	<0.0002	0.19	<0.001	0.355	4.35
9-69-77	1400	AMD-A	1.97	*	1.06	0.61	4.96	0.504	0.68	0.833	5.29	5.35
9-29-77	1400	AMD-B	1.63	*	0.917	0.53	4.32	0.479	0.60	0.658	4.97	5.15
9-29-77	1400	Product A	0.03	*	0.019	0.11	0.12	0.006	0.06	0.128	0.098	3.65
9-29-77	1400	Product B	0.04	*	0.067	0.12	0.15	0.010	0.19	0.043	0.197	3.45
9-29-77	1400	Sludge A	29.6	7.4	16.8	5.52	68.8	4.44	8.78	8.48	82.2	41.0
9-29-77	1400	Sludge B	8.78	4.0	5.76	2.16	24.2	4.06	2.60	3.80	28.8	13.6

(continued)

TABLE C-1 (Continued)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
9-30-77	0830	AMD	0.01	*	<0.001	0.09	0.02	<0.0002	0.17	<0.001	0.252	3.85
9-30-77	0830	AMD	1.95	*	0.557	0.52	4.37	0.553	0.57	0.823	4.55	5.70
9-30-77	0830	AMD-B	2.15	*	0.603	0.60	4.83	0.553	0.62	0.853	4.97	6.50
9-30-77	0830	Product A	0.04	*	0.014	0.10	0.10	0.009	0.06	0.149	0.086	1.65
9-30-77	0830	Product B	0.40	*	0.046	0.10	0.13	0.014	0.18	0.033	0.252	3.75
9-30-77	0830	Sludge A	34.4	2.1	16.1	6.72	86.4	5.32	10.0	10.9	96.4	47.4
9-30-77	0830	Sludge B	11.3	1.4	4.24	3.02	24.2	1.62	2.10	3.58	29.8	13.6
9-30-77	1500	AMD	0.01	*	<0.001	0.04	0.02	<0.0002	0.18	<0.001	0.273	2.40
9-30-77	1500	AMD-A	1.77	*	0.777	0.60	6.11	0.563	0.74	0.765	6.19	3.40
9-30-77	1500	AMD-B	2.06	*	0.777	0.55	6.30	0.548	0.75	0.950	6.40	3.10
9-30-77	1500	Product A	0.04	*	0.014	0.05	0.12	0.010	0.06	0.148	0.114	1.05
9-30-77	1500	Product B	0.04	*	0.053	0.05	0.18	0.016	0.21	0.048	0.273	1.40
9-30-77	1500	Sludge A	30.0	5.8	12.3	6.06	76.4	5.32	9.13	10.4	88.2	43.0
9-30-77	1500	Sludge B	6.04	6.4	2.88	1.32	10.6	0.95	1.74	1.90	21.6	7.20
10-1-77	0800	AMD	0.01	*	<0.001	0.04	0.02	<0.0002	0.18	<0.001	0.25	2.90
10-1-77	0800	AMD-A	1.95	*	0.707	0.51	5.30	0.533	0.65	0.931	5.44	3.50
10-1-77	0800	AMD-B	2.42	*	0.789	0.64	6.33	0.499	0.74	1.21	6.51	3.90
10-1-77	0800	Product A	0.04	*	0.017	0.07	0.13	0.012	0.20	0.210	0.165	1.50
10-1-77	0800	Product B	0.05	*	0.043	0.05	0.16	0.018	0.20	0.071	0.211	1.80
10-1-77	0800	Sludge A	32.0	5.9	11.8	5.88	70.0	4.53	8.75	10.7	83.2	40.0
10-1-77	0800	Sludge B	11.5	3.8	2.54	2.68	29.0	1.96	3.24	4.44	35.8	15.2
10-1-77	1500	AMD	0.03	*	<0.001	0.04	0.02	<0.0002	0.24	<0.001	0.446	2.70
10-1-77	1500	AMD-A	1.93	*	0.731	0.67	5.92	0.475	0.76	0.980	6.14	3.30
10-1-77	1500	AMD-B	2.00	*	0.777	0.72	6.49	0.484	0.80	1.18	6.57	3.90
10-1-77	1500	Product A	0.04	*	0.016	0.10	0.12	0.010	0.07	0.171	0.114	1.95
10-1-77	1500	Product B	0.04	*	0.042	0.10	0.19	0.017	0.20	0.086	0.260	1.90
10-1-77	1500	Sludge A	27.4	8.3	11.2	5.16	62.6	4.77	8.30	8.44	74.0	32.4
10-1-77	1500	Sludge B	8.14	7.8	3.50	1.82	19.2	1.38	2.05	3.42	22.6	10.2

(continued)

TABLE C-1 (Continued)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
						pH 7 (Process A) vs pH 12 (Process B)						
10-5-77	0830	AMD	0.01	0.6	<0.001	0.04	0.02	<0.0002	0.17	<0.001	0.249	2.15
10-5-77	0830	AMD-A	2.10	1.8	0.591	0.53	5.54	0.494	0.71	1.05	5.55	4.75
10-5-77	0830	AMD-B	1.84	2.0	0.545	0.42	3.98	0.450	0.50	0.833	4.14	4.75
10-5-77	0830	Product A	0.11	1.5	0.184	0.05	0.36	0.019	0.41	0.054	1.05	4.10
10-5-77	0830	Product B	0.02	0.8	0.048	0.05	0.08	0.012	0.06	0.136	0.126	0.45
10-5-77	0830	Sludge A	50.6	16.3	12.4	9.48	121.	7.56	6.91	15.2	115.	50.0
10-5-77	0830	Sludge B	16.3	11.8	4.44	2.60	42.6	2.85	6.78	7.00	53.8	11.0
10-5-77	1500	AMD	0.01	2.0	<0.001	0.03	0.02	0.0002	0.15	<0.001	0.267	2.70
10-5-77	1500	AMD-A	1.82	0.7	0.642	0.47	5.02	0.543	0.64	1.02	5.07	5.40
10-5-77	1500	AMD-B	2.11	1.8	0.719	0.46	5.15	0.475	0.63	1.01	5.29	4.30
10-5-77	1500	Product A	0.11	2.1	0.169	0.04	0.31	0.017	0.33	0.056	0.965	3.50
10-5-77	1500	Product B	0.02	1.0	0.003	0.04	0.06	0.018	0.06	0.158	0.068	1.50
10-5-77	1500	Sludge A	55.4	23.5	13.8	11.3	145.	8.70	7.30	17.8	131.	35.0
10-5-77	1500	Sludge B	13.3	12.1	4.44	2.16	34.0	2.57	5.26	5.16	43.8	9.25
10-6-77	0830	AMD	0.02	0.5	0.014	0.03	0.02	<0.0002	0.18	<0.001	0.311	5.40
10-6-77	0830	AMD-A	1.84	2.2	0.626	0.45	5.15	0.445	0.66	0.833	5.44	6.80
10-6-77	0830	AMD-B	2.08	1.7	0.511	0.37	4.27	0.499	0.54	0.980	4.45	7.15
10-6-77	0830	Product A	0.09	1.8	0.145	0.04	0.20	0.014	0.28	0.043	0.785	5.25
10-6-77	0830	Product B	0.02	1.4	0.003	0.05	0.09	0.007	0.07	0.158	0.308	1.35
10-6-77	0830	Sludge A	42.6	12.6	8.14	7.08	90.0	5.92	5.72	12.1	88.2	32.6
10-6-77	0830	Sludge B	2.08	10.9	1.66	0.72	5.62	0.54	0.58	0.82	6.74	2.73
10-6-77	1500	AMD	0.02	0.8	<0.001	0.02	0.04	<0.0002	0.15	<0.001	0.289	3.80
10-6-77	1500	AMD-A	1.99	2.8	0.696	0.50	5.78	0.509	0.71	0.882	5.82	5.40
10-6-77	1500	AMD-B	2.01	2.7	0.580	0.42	5.08	0.470	0.60	0.931	4.92	5.00
10-6-77	1500	Product A	0.10	2.5	0.172	0.04	0.35	0.014	0.34	0.031	0.979	3.45
10-6-77	1500	Product B	0.02	1.9	<0.001	0.04	0.10	0.003	0.05	0.119	0.048	1.20
10-6-77	1500	Sludge A	50.2	14.8	14.8	9.18	118.	7.75	7.17	16.2	115.	76.0
10-6-77	1500	Sludge B	9.46	13.1	3.90	1.82	20.4	1.77	2.80	2.82	23.4	11.2

(continued)

TABLE C-1 (Continued)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
10-7-77	0830	AMD	0.02	0.8	<0.001	0.03	0.04	<0.0002	0.18	<0.001	0.311	3.60
10-7-77	0830	AMD-A	2.24	2.6	0.603	0.46	5.15	0.523	0.63	1.01	5.02	5.20
10-7-77	0830	AMD-B	1.99	2.7	0.591	0.40	4.84	0.504	0.59	1.05	4.81	5.00
10-7-77	0830	Product A	0.10	2.7	0.193	0.03	0.35	0.015	0.38	0.037	1.05	3.35
10-7-77	0830	Product B	0.02	1.9	0.004	0.03	0.12	0.004	0.05	0.144	0.06	1.65
10-7-77	0830	Sludge A	46.0	12.0	12.8	8.42	109.	6.92	6.81	14.3	106.	60.0
10-7-77	0830	Sludge B	6.52	4.0	3.16	1.56	142.	1.38	2.44	2.40	18.3	8.75
10-7-77	1500	AMD	0.02	0.9	<0.001	0.02	0.03	<0.0002	0.19	<0.001	0.294	6.80
10-7-77	1500	AMD-A	2.06	3.3	0.825	0.58	6.05	0.476	0.73	1.07	6.94	10.3
10-7-77	1500	AMD-B	2.29	3.2	0.838	0.57	6.18	0.452	0.76	1.07	6.99	8.60
10-7-77	1500	Product A	0.09	2.9	0.191	0.03	0.25	0.015	0.37	0.040	1.05	2.40
10-7-77	1500	Product B	0.01	1.7	0.003	0.03	0.06	0.005	0.07	0.176	0.021	0.42
10-7-77	1500	Sludge A	28.6	18.8	8.96	6.24	79.6	5.37	5.08	19.8	80.4	46.0
10-7-77	1500	Sludge B	6.52	13.3	2.92	1.64	18.5	1.67	2.36	2.78	23.8	10.2
10-8-77	0830	AMD	0.01	*	<0.001	0.02	0.04	<0.0002	0.15	<0.001	0.206	6.20
10-8-77	0830	AMD-A	2.08	*	0.683	0.45	4.67	0.537	0.59	1.08	5.45	10.7
10-8-77	0830	AMD-B	1.99	*	0.670	0.45	4.67	0.490	0.57	1.11	5.40	11.6
10-8-77	0830	Product A	0.11	*	0.179	0.03	0.27	0.020	0.30	0.052	1.06	5.65
10-8-77	0830	Product B	0.02	*	0.003	0.03	0.05	0.015	0.05	0.149	0.059	0.90
10-8-77	0830	Sludge A	51.2	17.4	12.9	9.98	130.	9.34	6.60	18.4	111.	70.0
10-8-77	0830	Sludge B	6.04	11.4	2.38	1.46	14.8	1.19	2.42	2.34	17.8	9.23
10-8-77	1500	AMD	0.02	*	<0.001	0.02	0.01	<0.0002	0.14	<0.001	0.249	6.82
10-8-77	1500	AMD-A	1.92	*	0.709	0.47	4.92	0.447	0.60	1.13	5.55	7.66
10-8-77	1500	AMD-B	1.85	*	0.812	0.56	5.74	0.438	0.70	1.10	6.58	6.00
10-8-77	1500	Product A	0.11	*	0.185	0.03	0.29	0.014	0.31	0.061	1.14	2.80
10-8-77	1500	Product B	0.02	*	0.002	0.02	0.04	0.012	0.06	0.195	0.032	1.24
10-8-77	1500	Sludge A	44.8	16.8	12.9	8.90	126.	8.84	7.00	17.0	84.6	75.0
10-8-77	1500	Sludge B	8.04	15.2	2.66	1.34	17.9	2.24	2.26	3.68	18.8	10.0

*Sample was preserved with nitric acid and analysis was not possible because of interferences.

TABLE C-2. CONVENTIONAL POLLUTANT CHEMICAL ANALYSES FOR LIME NEUTRALIZATION

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Turb.
					pH 11 (Process A) vs pH 10 (Process B)												
9-19-77	0830	Raw feed	2850	370	4.7	340	100	155	130	340	12.0	5.1	2190	5	3140	3.0	48
9-19-77	0830	Spiked feed A	3030	430	3.6	340	100	160	160	340	8.4	5.2	2320	0	3270	2.7	51
9-19-77	0830	Spiked feed B	2900	460	4.4	340	100	160	160	330	8.0	5.2	2320	0	3260	3.5	53
9-19-77	0830	Effluent A	2900	0	11.0	600	6.9	1.7	0	330	.58	.16	2380	61	3320	11.2	10
9-19-77	0830	Effluent B	2880	0	10.0	600	25	1.6	0	330	.38	.15	2340	19	3290	5.5	3.5
9-19-77	1500	Raw feed	2950	470	5.2	340	100	160	150	330	8.6	4.6	2300	15	3240	3.6	34
9-19-77	1500	Spiked feed A	2950	470	5.0	330	95	160	150	320	6.0	4.5	2180	10	3090	1.5	63
9-19-77	1500	Spiked feed B	2950	470	5.0	340	96	150	140	330	6.0	4.5	2330	10	3240	7.7	64
9-19-77	1500	Effluent A	3000	0	10.8	680	7.1	1.2	0	330	.12	.10	2400	77	3410	5.0	18
9-19-77	1500	Effluent B	2880	0	9.8	530	25	.94	0	320	.16	.10	2210	41	3080	8.9	10
9-20-77	0830	Raw feed	2830	380	5.2	340	100	160	150	330	6.4	4.7	2340	18	3270	5.9	23
9-20-77	0830	Spiked feed A	2890	370	4.9	340	95	150	150	340	4.2	4.6	2330	5	3250	6.1	68
9-20-77	0830	Spiked feed B	2860	380	4.9	340	95	150	140	340	4.2	4.6	2330	5	3250	6.5	73
9-20-77	0830	Effluent A	3250	0	10.8	600	3.7	.16	0	330	.58	.05	2250	92	3190	8.8	15
9-20-77	0830	Effluent B	3150	0	9.9	500	20	.14	0	330	.80	.05	2050	41	2900	6.0	10
9-21-77	0830	Raw feed	2800	460	5.3	350	100	160	150	340	7.0	4.8	2350	25	3300	4.3	
9-21-77	0830	Spiked feed A	2800	460	5.0	350	100	160	150	320	4.8	4.8	2340	15	3270	5.7	
9-21-77	0830	Spiked feed B	2800	460	5.1	350	100	150	150	330	5.0	4.8	2340	20	3280	5.7	
9-21-77	0830	Effluent A	3000	0	11.2	680	4.4	.12	0	330	.32	.05	2440	120	3450	7.8	6
9-21-77	0830	Effluent B	3000	0	9.9	550	24	.18	0	330	.40	.05	2250	80	3150	9.6	10
9-21-77	1500	Raw feed	2800	430	5.3	350	95	150	150	340	8.6	4.78	2350	30	3300	5.7	
9-21-77	1500	Spiked feed A	2800	430	5.1	350	95	150	140	340	4.6	4.6	2340	20	3280	5.8	
9-21-77	1500	Spiked feed B	2800	430	5.1	350	90	150	150	330	22.	4.78	2500	25	3440	10.4	
9-21-77	1500	Effluent A	2900	0	10.8	580	6.5	.10	0	340	.46	.05	2400	80	3330	13.8	10
9-21-77	1500	Effluent B	2900	0	10.0	500	25	.16	0	340	.40	.05	2070	40	2940	4.5	12
Means		Raw feed	2720	450	5.2	340	100	160	150	350	6.3	5.0	2310	23	3260		35
		Spiked feed A	2700	450	4.9	340	98	160	150	340	5.4	5.0	2310	14	3250		61
		Spiked feed B	2730	450	5.0	350	98	150	150	340	6.6	5.0	2170	15	3330		63
		Effluent A	2840	0	10.9	610	5.0	.35	0	340	.40	.06	2340	90	3290		9
		Effluent B	2840	0	10.0	530	25	.40	0	340	.40	.06	2250	50	3160		7

(continued)

TABLE C-2 (Continued)

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Turb.
9-22-77	0830	Raw Feed	2600	510	5.1	340	90	170	160	330	4.0	4.8	2180	15	3110	1.7	
9-22-77	0830	Spiked feed A	2600	510	4.8	340	90	170	160	330	4.0	4.8	2330	5	3250	6.9	
9-22-77	0830	Spiked feed B	2600	420	4.9	340	90	170	160	330	4.0	4.8	2330	10	3260	7.3	
9-22-77	0830	Effluent A	2740	0	10.8	600	5.8	.10	0	330	.18	.05	2130	92	3060	2.5	10
9-22-77	0830	Effluent B	2690	0	9.9	520	23	.20	0	330	.24	.08	2080	46	2950	4.2	7.7
9-22-77	1500	Raw feed	2800	550	5.2	350	100	170	160	350	6.0	4.9	2210	20	3180	2.5	
9-22-77	1500	Spiked feed A	2800	500	5.0	350	100	170	160	350	8.4	4.8	2330	10	3310	1.2	
9-22-77	1500	Spiked feed B	2800	500	5.0	350	100	170	160	350	6.8	4.9	2480	10	3460	6.9	
9-22-77	1500	Effluent A	3000	0	10.8	660	3.7	.06	0	330	.42	.05	2280	90	3280	3.1	12
9-22-77	1500	Effluent B	3000	0	10.0	600	25	.12	0	330	.56	.05	2400	45	3350	8.4	5
9-23-77	0830	Raw feed	2600	480	5.2	370	100	170	160	350	6.6	4.7	2490	20	3490	6.3	
9-23-77	0830	Spiked feed A	2500	480	5.1	370	96	170	160	340	6.6	4.7	2350	26	3320	2.9	
9-23-77	0830	Spiked feed B	2500	480	5.0	370	98	160	160	340	6.2	4.7	2345	15	3310	2.1	
9-23-77	0830	Effluent A	2400	0	10.8	650	5.0	.18	0	330	.05	.05	2420	97	3400	9.4	4.0
9-23-77	0830	Effluent B	2700	0	9.8	540	24	.20	0	330	.05	.05	2370	51	3260	13.8	4.0
9-23-77	1500	Raw feed	2550	360	5.5	310	110	140	130	360	2.5	5.1	2360	41	3280	9.3	
9-23-77	1500	Spiked feed A	2250	410	5.3	310	100	140	130	360	5.1	5.1	2190	26	3110	1.8	
9-23-77	1500	Spiked feed B	2750	450	5.3	360	110	130	130	350	2.7	5.0	2350	31	3300	5.3	
9-23-77	1500	Effluent A	2700	0	11.0	540	3.0	.15	0	340	.40	.05	2220	87	3100	11.8	4.0
9-23-77	1500	Effluent B	2800	0	10.0	500	26	1.0	0	350	.40	.05	2410	51	3290	16.7	7.0
9-24-77	0830	Raw feed	2500	500	5.1	320	100	160	150	350	4.1	5.8	2350	31	3290	7.4	
9-24-77	0830	Spiked feed A	2450	520	5.1	320	100	160	150	350	5.1	5.9	2340	18	3270	6.2	
9-24-77	0830	Spiked feed B	2450	520	5.0	340	100	160	150	350	3.9	5.9	2490	15	3460	8.9	
9-24-77	0830	Effluent A	2600	0	10.9	620	4.0	.07	0	350	.54	.05	2410	92	3380	10.7	3.5
9-24-77	0830	Effluent B	2500	0	9.5	510	28	.12	0	370	.70	.06	2220	56	3130	7.0	5.8
9-24-77	1500	Raw feed	2600	400	5.4	340	110	150	150	380	3.8	5.9	2300	36	3290	0.2	
9-24-77	1500	Spiked feed A	2600	410	5.2	330	110	150	150	370	3.0	5.9	2340	20	3300	3.7	
9-24-77	1500	Spiked feed B	2600	420	5.3	340	100	140	140	350	3.7	5.9	2340	20	3320	2.2	
9-24-77	1500	Effluent A	2770	0	10.8	540	4.7	.05	0	370	.30	.05	2410	92	3330	15.8	4.0
9-24-77	1500	Effluent B	2720	0	10.5	520	30	.07	0	420	.36	.05	2410	92	3380	10.3	7.0

(continued)

TABLE C-2 (Continued)

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Turb.
		pH 9 (Process A) vs pH 8 (Process B)															
9-27-77	0830	Raw feed	2430	390	5.2	330	110	170	160	340	6.7	5.8	2350	31	3310	5.0	
9-27-77	0830	Spiked feed A	2450	400	5.1	330	110	160	160	350	19.	5.9	2340	20	3310	1.2	
9-27-77	0830	Spiked feed B	2450	410	5.2	345	110	160	160	350	7.8	5.9	2340	20	3300	4.0	
9-27-77	0830	Effluent A	2500	0	9.0	480	70	.35	0	340	.38	.20	2210	43	3100	4.4	10
9-27-77	0830	Effluent B	2580	0	7.8	480	100	.63	0	340	.20	2.6	2430	32	3360	10.6	10
9-27-77	1500	Raw feed	2550	360	5.2	340	110	160	160	350	6.4	4.9	2350	31	3310	4.4	
9-27-77	1500	Spiked feed A	2550	380	5.2	330	100	160	160	350	8.0	5.0	2340	18	3290	4.5	
9-27-77	1500	Spiked feed B	2540	380	5.2	330	100	160	160	350	14	5.0	2340	20	3290	3.6	
9-27-77	1500	Effluent A	2550	0	8.8	480	70	.28	0	340	.26	.17	2210	46	3100	4.9	10
9-27-77	1500	Effluent B	2620	0	8.0	480	100	.53	0	340	.12	2.3	2440	37	3360	11.1	12
9-28-77	0830	Raw feed	2560	350	5.4	340	100	150	150	360	5.9	5.0	2350	36	3310	5.6	
9-28-77	0830	Spiked feed A	2530	370	5.3	320	100	150	150	350	5.5	5.2	2340	26	3280	6.5	
9-28-77	0830	Spiked feed B	2530	370	5.3	320	100	150	150	350	4.7	5.4	2340	20	3270	7.0	
9-28-77	0830	Effluent A	2500	0	8.8	450	73	.37	0	340	.16	.22	2210	46	3070	7.8	13
9-28-77	0830	Effluent B	2640	0	7.9	470	98	.77	0	350	.18	2.4	2300	33	3210	7.7	13
9-28-77	1500	Raw feed	2530	370	5.3	340	100	160	160	340	4.6	5.0	2350	31	3300	5.7	
9-28-77	1500	Spiked feed A	2550	370	5.2	340	100	150	150	340	7.2	4.9	2340	15	3280	4.8	
9-28-77	1500	Spiked feed B	2580	310	5.2	330	100	150	150	340	5.6	5.1	2340	20	3280	6.2	
9-28-77	1500	Effluent A	2600	0	8.8	460	72	.35	0	330	.16	.25	2210	43	3077	7.8	10
9-28-77	1500	Effluent B	2700	0	8.0	480	100	.49	0	340	.22	2.5	2300	33	3220	6.7	10
9-29-77	0830	Raw feed	2390	380	5.2	340	100	160	160	330	7.1	5.5	2360	43	3310	6.4	
9-29-77	0830	Spiked feed A	2380	380	5.0	340	100	160	160	330	6.9	5.6	2330	10	3280	3.9	
9-29-77	0830	Spiked feed B	2380	350	5.0	340	100	160	160	330	7.1	5.7	2330	10	3280	3.9	
9-29-77	0830	Effluent A	2350	0	9.2	490	64	.51	0	330	.40	.22	2210	41	3080	6.3	10
9-29-77	0830	Effluent B	2500	0	8.0	500	100	.67	0	340	.42	2.8	2440	37	3380	8.8	10
9-29-77	1500	Raw feed	2500	380	5.2	360	98	160	160	370	8.8	5.2	2350	26	3350	1.0	
9-29-77	1500	Spiked feed A	2500	350	5.1	360	95	160	140	360	8.8	5.2	2350	15	3330	1.3	
9-29-77	1500	Spiked feed B	2500	370	5.1	360	96	160	140	360	7.6	5.2	2350	15	3330	1.4	
9-29-77	1500	Effluent A	2450	0	9.0	550	55	.18	0	340	.42	.17	2250	41	3200	1.5	7.3
9-29-77	1500	Effluent B	2600	0	7.9	510	90	.38	0	340	.42	2.6	2280	37	3220	3.5	10

(continued)

TABLE C-2 (Continued)

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Turb.
9-30-77	0830	Raw feed	2300	370	5.3	360	100	160	160	370	7.8	5.3	2500	26	3500	6.7	
9-30-77	0830	Spiked feed A	2350	370	5.2	360	100	160	160	370	7.6	5.3	2500	10	3500	6.1	
9-30-77	0830	Spiked feed B	2350	320	5.2	360	100	160	160	370	7.2	5.6	2500	13	3500	6.3	
9-30-77	0830	Effluent A	2300	0	9.0	400	60	.20	0	340	.44	.18	2000	41	2800	6.1	10
9-30-77	0830	Effluent B	2480	0	7.8	380	95	.40	0	350	.54	2.7	2050	37	2880	6.0	10
9-30-77	1500	Raw feed	2440	320	5.5	340	95	150	150	360	2.8	5.4	2250	51	3200	3.0	
9-30-77	1500	Spiked feed A	2440	310	5.4	340	95	130	130	360	2.8	5.4	2250	31	3180	3.5	
9-30-77	1500	Spiked feed B	2400	310	5.5	340	95	130	130	360	3.8	5.4	2250	31	3180	3.3	
9-30-77	1500	Effluent A	2350	0	8.9	500	55	.60	0	340	.64	.18	2150	46	3040	3.0	10
9-30-77	1500	Effluent B	2530	0	7.8	460	90	.85	0	340	.72	2.8	2200	47	3090	5.9	10
10-1-77	0830	Raw feed	2400	460	5.2	350	95	160	160	350	4.6	6.2	2300	15	3270	2.1	
10-1-77	0830	Spiked feed A	2400	460	5.1	350	95	160	160	350	4.6	6.2	2300	20	3270	2.3	
10-1-77	0830	Spiked feed B	2400	460	5.1	350	95	160	160	350	4.6	6.1	2300	20	3270	2.3	
10-1-77	0830	Effluent A	2300	0	8.9	490	60	.40	0	340	.10	.20	2100	40	2990	0.9	13
10-1-77	0830	Effluent B	2300	0	7.9	450	90	1.6	0	340	.20	2.3	2150	30	3030	4.6	11
10-1-77	1500	Raw feed	2500	650	4.7	350	110	200	200	300	14.	4.9	2400	0	3380	2.7	
10-1-77	1500	Spiked feed A	2500	650	4.3	350	110	200	200	290	20	4.9	2400	0	3370	2.0	
10-1-77	1500	Spiked feed B	2500	645	4.3	350	110	200	200	290	15	4.9	2400	0	3370	3.2	
10-1-77	1500	Effluent A	2400	0	9.0	480	65	.08	0	300	.22	.15	2050	50	2900	2.7	10
10-1-77	1500	Effluent B	2400	0	7.9	420	100	.18	0	300	.28	1.7	2050	40	2870	5.5	10
Means		Raw feed	2460	400	5.2	350	100	160	160	350	6.9	5.3	2360	29	3320		
		Spiked feed A	2470	400	5.1	340	100	160	160	350	9.0	5.3	2350	17	3310		
		Spiked feed B	2460	400	5.1	340	100	160	160	350	7.7	5.4	2350	17	3310		
		Effluent A	2430	0	8.9	480	64	.33	0	330	.31	.19	2160	44	3040		10
		Effluent B	2540	0	7.9	460	96	.65	0	340	.33	2.5	2020	36	3160		11

(continued)

TABLE C-2 (Continued)

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Turb.
								pH 7 (Process A) vs pH 12 (Process B)									
10-4-77	0830	Raw feed	2500	500	5.2	380	110	160	160	350	8.2	4.9	2490	15	3500	4.4	
10-4-77	0830	Spiked feed A	2500	500	5.0	370	110	160	160	350	22	4.8	2480	10	3480	2.8	
10-4-77	0830	Spiked feed B	2500	480	5.0	360	100	160	160	350	16	4.8	2480	10	3470	5.3	
10-4-77	0830	Effluent A	2500	18	7.0	480	98	1.0	0	330	.44	3.6	2360	40	3270	6.4	25
10-4-77	0830	Effluent B	6200	0	12.0	1050	.05	.05	0	340	.16	.05	3550	1290	4940	32.6	3.0
10-4-77	1500	Raw feed	2500	460	5.3	375	100	150	150	360	7	4.9	2500	30	3500	6.7	
10-4-77	1500	Spiked feed A	2500	470	5.2	365	100	150	150	350	22	4.9	2490	20	3480	4.7	
10-4-77	1500	Spiked feed B	2500	500	5.3	375	100	150	150	350	19	4.8	2490	15	3490	3.9	
10-4-77	1500	Effluent A	2500	0	7.2	485	98	.75	0	340	.40	3.6	2370	50	3290	6.3	25
10-4-77	1500	Effluent B	6600	0	12.0	1000	.05	.05	0	340	.20	.05	3560	1390	4900	36.3	3.5
10-5-77	0830	Raw feed	2500	420	5.6	380	100	150	140	370	4.0	5.0	2510	40	3510	7.7	
10-5-77	0830	Spiked feed A	2500	420	5.3	370	100	140	140	370	18	4.9	2500	25	3500	4.4	
10-5-77	0830	Spiked feed B	2500	420	5.3	370	100	140	140	370	18	4.9	2510	25	3500	6.0	
10-5-77	0830	Effluent A	2500	25	6.4	470	96	1.2	0	360	.42	3.6	2380	50	3310	6.1	25
10-5-77	0830	Effluent B	6400	0	12.1	1040	.06	.05	0	370	.24	.05	3410	1400	4810	31.3	3.0
10-5-77	1500	Raw feed	2700	450	5.3	380	100	150	150	370	5.6	4.8	2350	25	3360	0.1	
10-5-77	1500	Spiked feed A	2700	460	5.1	370	100	150	150	370	14	4.8	2500	15	3500	5.4	
10-5-77	1500	Spiked feed B	2700	460	5.1	360	100	150	150	360	8.0	4.8	2340	15	3320	1.1	
10-5-77	1500	Effluent A	2700	12	7.0	450	96	1.3	0	350	.60	3.8	2370	45	3270	8.9	34
10-5-77	1500	Effluent B	6000	0	12.3	860	.06	.05	0	350	.46	.05	3230	1070	4440	34.2	2.7
10-6-77	0830	Raw feed	2700	520	5.0	380	100	170	170	350	8.8	4.9	2500	10	3500	5.0	
10-6-77	0830	Spiked feed A	2700	530	4.8	360	98	170	170	350	9.0	5.0	2490	5	3480	6.2	
10-6-77	0830	Spiked feed B	2700	530	4.8	370	98	170	170	350	8.8	5.0	2490	5	3490	6.0	
10-6-77	0830	Effluent A	2700	12	6.9	500	90	1.3	0	340	.50	3.7	2370	40	3300	5.5	20
10-6-77	0830	Effluent B	6000	0	12.2	960	.05	.05	0	340	.40	.05	3550	1220	4850	36.0	3.0
10-6-77	1500	Raw feed	2700	470	5.1	380	110	160	150	350	8.0	4.7	2510	20	3500	5.8	
10-6-77	1500	Spiked feed A	2700	470	4.9	380	110	170	150	350	10	4.7	2490	5	3500	3.7	
10-6-77	1500	Spiked feed B	2700	480	4.9	370	100	160	150	350	7.8	4.7	2490	5	3470	6.5	
10-6-77	1500	Effluent A	2700	12	7.0	480	95	2.5	0	310	.32	3.6	2520	35	3410	14.6	22
10-6-77	1500	Effluent B	6200	0	12.0	900	.06	.05	0	310	.20	.05	3410	1230	4620	38.7	3.0

(continued)

TABLE C-2 (Concluded)

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Turb.
10-7-77	0830	Raw feed	2600	520	5.2	370	100	150	150	360	7.2	4.52	2660	15	3640	13.1	
10-7-77	0830	Spiked feed A	2600	460	5.0	370	100	150	150	350	7.0	4.52	2660	10	3630	13.2	
10-7-77	0830	Spiked feed B	2600	460	5.0	360	100	150	150	350	7.0	4.52	2660	10	3630	13.6	
10-7-77	0830	Effluent A	2600	6	7.1	480	97	2.4	0	330	.40	3.68	2690	40	3590	18.4	25
10-7-77	0830	Effluent B	5600	0	12.2	1000	.09	.05	0	320	.24	<.05	2860	1210	4180	23.6	3.0
10-7-77	1500	Raw feed	2700	430	5.6	340	100	130	130	380	5.0	4.74	2280	55	3240	2.7	
10-7-77	1500	Spiked feed A	2700	370	5.4	340	100	130	130	380	8.0	4.74	2250	30	3210	0.2	
10-7-77	1500	Spiked feed B	2700	400	5.4	340	100	130	130	380	4.8	4.68	2260	35	3210	1.4	
10-7-77	1500	Effluent A	2700	6	7.1	440	90	1.1	0	330	.28	3.70	2300	80	3160	12.0	25
10-7-77	1500	Effluent B	5800	0	12.2	1000	.05	.10	0	350	.10	<.05	2750	1190	4100	19.3	3.0
10-8-77	0830	Raw feed	2600	410	5.4	360	100	155	150	360	5.8	4.8	2410	15	3390	4.0	
10-8-77	0830	Spiked feed A	2700	430	5.2	350	100	150	150	360	6.0	4.8	2410	15	3380	5.3	
10-8-77	0830	Spiked feed B	2550	510	5.2	350	100	150	150	360	5.4	4.8	2400	13	3370	5.8	
10-8-77	0830	Effluent A	2700	25	6.8	470	95	2.7	2.5	350	.40	3.7	2450	62	3370	10.7	20
10-8-77	0830	Effluent B	5150	0	12.4	960	.05	0	0	360	.10	.05	3000	1043	4320	23.5	1.5
10-8-77	1500	Raw feed	2600	660	4.8	350	100	200	200	340	10	5.1	2410	10	3410	2.2	
10-8-77	1500	Spiked feed A	2650	610	4.6	350	100	190	181	340	15	5.1	2400	5	3390	1.6	
10-8-77	1500	Spiked feed B	2700	680	4.7	350	100	190	181	340	17	5.1	2410	5	3400	1.9	
10-8-77	1500	Effluent A	2700	12	6.8	470	95	.05	0	340	.42	3.7	2250	31	3160	2.9	21
10-8-77	1500	Effluent B	5600	0	12.3	940	.05	.05	0	340	.24	.05	3000	1158	4280	27.7	.5
Means		Raw feed	2610	480	5.2	370	100	160	160	360	7.0	4.8	2240	24	3460		
		Spiked feed A	2625	460	5.1	360	101	160	150	360	13.	4.8	2470	13	3460		
		Spiked feed B	2615	490	5.1	360	100	160	150	360	11.2	4.8	2450	14	3440		
		Effluent A	2630	13	6.9	470	100	1.4	.25	340	.42	3.7	2400	47	3310		
		Effluent B	5960	0	12.1	970	.06	.05	0	340	.23	.05	3230	1220	4540		

All units are mg/l except for pH, specific conductance (μmhos/cm), and turbidity (FTU).
*Ion balance expressed as percent difference between cations and anions (converted to $CaCO_3$).

TABLE C-3. MATERIAL BALANCE FOR LIME NEUTRALIZATION STUDY
(ratio of influent: effluent)

Parameter	Nominal pH					
	7	8	9	10	11	12
Arsenic	0.43	1.67	0.64	1.37	0.91	1.67
Boron	0.66	-	-	1.50	0.92	0.80
Cadmium	0.49	1.32	0.55	1.24	0.86	1.45
Chromium	0.53	1.87	0.87	1.61	1.31	1.72
Copper	0.45	1.90	0.71	1.57	1.09	0.95
Mercury	0.65	2.05	0.95	2.29	1.47	1.82
Nickel	0.69	1.46	0.68	1.38	0.97	1.25
Phosphorus	0.78	1.61	0.90	3.83	2.57	2.97
Selenium	0.61	2.32	0.78	1.48	1.28	1.68
Zinc	0.50	1.57	0.64	1.39	1.01	1.43

TABLE C-4. REVERSE OSMOSIS TRACE ELEMENT ANALYSES
(mg/l)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
10-12-77	0940	Raw AMD	0.01	0.4	<0.001	0.02	0.01	<0.0002	0.13	<0.001	0.220	0.48
10-12-77	0940	Spiked AMD	2.22	2.2	0.775	0.54	6.38	0.281	0.77	0.752	6.81	1.54
10-12-77	0940	Product	0.02	1.0	0.032	<0.01	0.01	0.035	<0.01	0.130	0.017	0.28
10-12-77	0940	Brine	3.57	3.0	1.18	0.83	9.41	0.162	1.16	2.02	11.1	1.80
10-12-77	1010	Raw AMD	0.01	0.5	<0.001	0.01	0.01	<0.0002	0.12	<0.001	0.220	0.46
10-12-77	1010	Spiked AMD	2.17	2.0	0.903	0.57	6.50	0.256	0.76	1.15	7.20	1.50
10-12-77	1010	Product	0.01	0.8	0.002	<0.01	<0.01	0.047	<0.01	0.116	0.024	0.12
10-12-77	1010	Brine	3.29	3.1	1.28	0.83	9.48	0.166	1.16	1.88	10.4	1.84
10-12-77	1040	Raw AMD	0.01	0.4	<0.001	0.02	0.01	<0.0002	0.14	<0.001	0.247	0.48
10-12-77	1040	Spiked AMD	2.26	1.9	0.812	0.51	6.18	0.260	0.71	1.23	6.58	1.70
10-12-77	1040	Product	0.02	0.6	0.002	0.01	0.01	0.048	<0.01	0.100	0.042	0.30
10-12-77	1040	Brine	3.73	3.2	0.967	0.59	7.26	0.175	0.85	1.52	7.83	1.82
10-12-77	1110	Raw AMD	0.01	0.5	0.012	0.02	0.02	<0.0002	0.15	<0.001	0.276	0.98
10-12-77	1110	Spiked AMD	2.21	2.0	0.750	0.46	5.68	0.279	0.68	1.07	6.14	1.50
10-12-77	1110	Product	0.02	0.7	0.002	<0.01	0.02	0.055	0.01	0.090	0.052	0.18
10-12-77	1110	Brine	3.57	3.5	1.27	0.79	9.66	0.183	1.16	1.71	10.5	2.20
10-12-77	1140	Raw AMD	0.01	0.4	0.060	0.02	0.01	<0.0002	0.13	0.002	0.234	0.80
10-12-77	1140	Spiked AMD	2.32	2.1	0.892	0.55	6.59	0.264	0.80	1.31	6.24	1.54
10-12-77	1140	Product	0.01	0.9	0.002	<0.01	0.02	0.056	0.01	0.111	0.060	0.56
10-12-77	1140	Brine	3.43	3.2	1.10	0.65	8.30	0.190	0.98	2.00	8.74	2.02
10-12-77	1210	Raw AMD	0.01	0.6	0.010	0.01	0.01	<0.0002	0.14	<0.001	0.245	0.54
10-12-77	1210	Spiked AMD	2.03	2.1	0.760	0.47	5.78	0.266	0.66	1.18	5.61	1.16
10-12-77	1210	Product	0.01	1.0	0.006	<0.01	0.01	0.067	<0.01	0.121	0.149	0.32
10-12-77	1210	Brine	4.23	3.2	1.31	0.93	9.69	0.179	1.19	1.71	10.7	1.72
10-12-77	1240	Raw AMD	0.01	0.6	<0.001	0.02	0.01	0.0003	0.13	<0.001	0.198	0.74
10-12-77	1240	Spiked AMD	2.53	2.1	0.887	0.68	6.38	0.247	0.81	1.29	5.87	2.02
10-12-77	1240	Product	0.01	1.0	0.002	<0.01	0.01	0.072	<0.01	0.135	0.034	0.26
10-12-77	1240	Brine	3.85	2.9	1.41	0.95	10.6	0.152	1.24	1.92	10.4	2.96

(continued)

TABLE C-4. (Continued)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
10-12-77	1310	Raw AMD	0.01	0.7	<0.001	0.02	0.01	<0.0002	0.16	<0.001	0.269	0.80
10-12-77	1310	Spiked AMD	2.42	1.8	0.897	0.60	6.44	0.316	0.78	1.20	6.53	1.98
10-12-77	1310	Product	0.01	1.0	0.004	<0.01	0.02	0.070	<0.01	0.122	0.048	0.46
10-12-77	1310	Brine	3.33	2.8	1.26	0.83	9.33	0.149	1.11	1.78	9.25	2.00
10-12-77	1340	Raw AMD	0.01	0.7	<0.001	0.02	0.01	<0.0002	0.13	<0.001	0.245	0.96
10-12-77	1340	Spiked AMD	2.37	1.7	0.836	0.53	6.23	0.292	0.73	1.30	6.05	1.04
10-12-77	1340	Product	0.01	0.6	0.002	<0.01	<0.01	0.051	<0.01	0.113	0.074	0.30
10-12-77	1340	Brine	3.27	2.5	1.11	0.91	8.22	0.171	1.05	1.90	8.14	1.44
10-12-77	1410	Raw AMD	0.01	0.6	0.031	0.02	0.02	<0.0002	0.14	<0.001	0.226	0.76
10-12-77	1410	Spiked AMD	2.39	2.2	0.765	0.51	5.65	0.307	0.69	1.25	5.48	1.02
10-12-77	1410	Product	0.01	1.2	0.003	<0.01	<0.01	0.101	<0.01	0.111	0.064	0.46
10-12-77	1410	Brine	3.51	3.4	1.27	0.87	9.28	0.205	1.14	1.90	9.20	1.54
Mean		Raw AMD	0.01	0.54	0.012	0.02	0.02	0.0002	0.14	0.001	0.238	0.700
Std.dev.		Raw AMD	(0)	(0.12)	(0.019)	(0.00)	(0.00)	(0.0)	(0.01)	(0)	(0.024)	(0.198)
Mean		Spiked AMD	-2.29	2.01	0.828	0.54	6.18	0.277	0.74	1.17	6.25	1.500
Std.dev.		Spiked AMD	(0.14)	(0.17)	(0.063)	(0.06)	(0.35)	0.023	(0.05)	(0.17)	(0.538)	(0.350)
Mean		Product	0.01	0.88	0.006	0.01	0.01	0.060	0.01	0.11	0.056	0.324
Std.dev.		Product	(0.00)	(0.20)	(0.009)	(0.0)	(0.0)	(0.018)	(0)	(0.01)	(0.037)	(0.134)
Mean		Brine	3.58	3.08	1.22	0.82	9.12	0.173	1.10	1.83	9.63	1.934
Std.dev.		Brine	(0.30)	(0.29)	(0.13)	(0.12)	(0.95)	(0.017)	(0.12)	(0.15)	(1.15)	(0.424)

TABLE C-5. REVERSE OSMOSIS CONVENTIONAL POLLUTANT ANALYSES

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal
10-12-77	0940	Raw AMD	2800	340	5.4	370	110	160	140	410	4.8	4.9	2440	46	3500	1.0
10-12-77	0940	Spiked feed	6200	1420	2.1	370	110	160	140	430	4.8	4.7	3090	0	4170	5.2
10-12-77	0940	Brine	8500	2000	2.0	600	190	270	230	680	6.6	6.9	4570	0	6320	1.8
10-12-77	0940	Product	78	99	3.6	.50	.16	.18	0	.22	.20	<.05	9.6	0	10	40.0
10-12-77	1010	Raw AMD	2800	380	5.4	370	110	160	140	410	4.0	4.9	2440	46	3500	0.8
10-12-77	1010	Spiked feed	6000	1320	2.1	360	110	160	140	410	4.0	4.7	3090	0	4140	7.5
10-12-77	1010	Brine	8400	1930	2.0	580	180	260	230	650	6.6	6.9	4570	0	6250	2.1
10-12-77	1010	Product	64	110	3.6	.68	.20	.24	0	.26	.30	.05	12	0	10	30.1
10-12-77	1040	Raw AMD	2800	380	5.4	360	110	160	140	410	5.0	4.9	2440	46	3490	0.6
10-12-77	1040	Spiked feed	6200	1340	2.1	360	110	160	140	410	4.8	4.7	3090	0	4150	7.0
10-12-77	1040	Brine	8600	2030	2.0	590	170	260	230	640	6.8	6.9	4570	0	6240	2.5
10-12-77	1040	Product	60	110	3.6	.62	.20	.24	0	.40	.40	.05	16	0	20	11.3
10-12-77	1110	Raw AMD	2800	380	5.4	370	110	160	140	420	4.2	5.0	2440	46	3500	1.3
10-12-77	1110	Spiked feed	6000	1300	2.1	370	120	160	140	420	4.2	4.9	3090	0	4160	5.7
10-12-77	1110	Brine	8500	2030	2.0	600	190	260	230	630	6.8	7.1	4730	0	6420	4.9
10-12-77	1110	Product	74	124	3.6	.76	.25	.30	0	.40	.20	.05	22	0	20	19.7
10-12-77	1140	Raw AMD	2800	350	5.4	370	110	170	150	410	4.4	5.0	2770	46	3830	10.4
10-12-77	1140	Spiked feed	6000	1300	2.1	370	110	170	140	400	4.4	4.9	3090	0	4150	6.9
10-12-77	1140	Brine	8400	1980	2.0	590	180	260	230	620	6.4	7.1	4570	0	6220	3.4
10-12-77	1140	Product	64	124	3.6	.70	.24	.30	0	.40	.26	.05	26	0	30	31.5
10-12-77	1210	Raw AMD	2800	360	5.4	370	110	170	150	410	4.0	5.0	2770	46	3830	10.9
10-12-77	1210	Spiked feed	6000	1350	2.1	370	110	170	150	400	4.0	5.0	3090	0	4140	7.4
10-12-77	1210	Brine	8800	2130	2.0	590	180	270	230	630	6.2	7.1	4400	0	6070	0.8
10-12-77	1210	Product	62	110	3.6	.54	.20	.30	0	.24	.16	<.05	26	0	30	37.0

(continued)

TABLE C-5. (Continued)

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal
10-12-77	1240	Raw AMD	2800	420	5.3	370	110	170	150	400	5.2	5.1	2440	30	3490	1.3
10-12-77	1240	Spiked feed	6000	1280	2.3	370	110	170	150	400	5.2	4.9	2900	0	3960	5.5
10-12-77	1240	Brine	8600	2150	2.0	600	180	280	240	640	7.6	7.1	4890	0	6600	7.0
10-12-77	1240	Product	62	86	3.5	.65	.22	.32	0	.32	.24	.05	22	0	20	6.8
10-12-77	1310	Raw AMD	2600	450	5.2	380	110	180	150	410	6.8	5.1	2600	20	3690	1.7
10-12-77	1310	Spiked feed	5600	1300	2.1	380	110	180	150	420	6.8	5.0	3090	0	4180	4.0
10-12-77	1310	Brine	8400	2050	2.0	600	180	280	240	640	11	7.2	4730	0	6440	4.0
10-12-77	1310	Product	62	190	3.6	.60	.21	.32	0	.24	.24	.05	26	0	30	34.4
10-12-77	1340	Raw AMD	2500	450	5.3	360	110	170	150	390	6.6	5.2	2600	20	3630	6.9
10-12-77	1340	Spiked feed	6000	1400	2.3	360	110	170	150	390	6.6	5.0	2800	0	3830	4.3
10-12-77	1340	Brine	8500	2060	2.1	580	180	280	240	630	11	7.2	4570	0	6250	3.9
10-12-77	1340	Product	58	190	3.6	.62	.23	.35	0	.36	.24	.05	30	0	30	41.6
10-12-77	1410	Raw AMD	2500	450	5.4	350	110	170	150	400	6.0	5.1	2550	20	3580	5.3
10-12-77	1410	Spiked feed	5800	1340	2.4	350	110	170	150	400	5.6	4.9	2770	0	3800	5.1
10-12-77	1410	Brine	8600	2210	2.2	580	170	270	240	620	9.0	7.3	4500	0	6160	5.7
10-12-77	1410	Product	58	120	3.5	.75	.24	.38	0	.40	.16	.05	30	0	30	30.9
10-12-77	1440	Raw AMD	2800	450	5.4	360	110	170	150	400	4.2	5.3	2440	20	3480	0.4
10-12-77	1440	Spiked feed	6000	1410	2.3	360	110	170	150	400	4.2	5.0	2770	0	3810	2.8
10-12-77	1440	Brine	8600	2160	2.1	570	170	270	240	610	7.6	7.2	4570	0	6200	6.8
10-12-77	1440	Product	58	170	3.6	.56	.20	.30	0	.20	.14	.06	28	0	30	41.9
Mean		Raw AMD	2730	400	5.36	400	110	170	150	400	5.0	5.1	2540	35	3620	
		Blend	5980	1340	2.2	365	110	170	150	400	5.0	50	2990	0	4040	
		Brine	8540	2070	2.0	590	180	270	230	640	7.8	7.1	4610	0	6290	
		Product	60	130	3.6	.60	.20	.30	-	.30	.20	.05	22	0	24	

All units are mg/l except for pH, specific conductance (μmhos/cm), and ion balance (expressed as a percent difference between cations and anions as $CaCO_3$).

TABLE C-6. MATERIAL BALANCE FOR REVERSE OSMOSIS STUDY
(ratio of influent: effluent)

Parameter	Ratio
Arsenic	1.03
Boron	0.90
Cadmium	1.09
Chromium	1.05
Copper	1.09
Mercury	2.18
Nickel	1.08
Phosphorus	1.14
Selenium	0.99
Zinc	1.04
Acidity	1.01
Aluminum	1.02
Calcium	1.01
Iron, ferrous	1.05
Iron, total	1.01
Magnesium	0.98
Manganese	1.13
Sodium	1.01
Specific conductance	1.12
Sulfate	1.04
Total dissolved solids	1.03

TABLE C-7. ION EXCHANGE TRACE ELEMENT ANALYSES
(mg/l)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
10-12-77	1000	Raw AMD	0.01	0.5	<0.001	0.03	0.02	<0.0002	0.18	<0.001	0.257	1.50
10-12-77	1000	Spiked AMD	2.29	2.1	0.884	0.61	7.29	0.566	0.90	1.29	7.41	2.07
10-12-77	1000	Cation effluent	1.54	1.9	0.009	0.04	0.17	0.034	0.02	1.04	0.145	18.2
10-12-77	1000	Anion effluent	0.58	1.3	<0.001	<0.01	0.02	0.0004	0.02	0.090	0.025	13.9
10-12-77	1045	Raw AMD	0.01	0.5	<0.001	0.01	0.05	<0.0002	0.19	<0.001	0.436	0.72
10-12-77	1045	Spiked AMD	2.48	2.1	0.884	0.61	7.04	0.692	0.83	1.29	7.08	1.22
10-12-77	1045	Cation effluent	1.66	1.7	0.010	0.05	0.21	0.026	0.02	1.24	0.253	14.0
10-12-77	1045	Anion effluent	0.40	0.2	0.001	0.01	0.08	0.0003	0.01	0.054	0.08	9.59
10-12-77	1115	Raw AMD	0.01	0.3	0.001	0.02	0.06	<0.0002	0.18	<0.001	0.666	0.70
10-12-77	1115	Spiked AMD	2.71	2.1	0.922	0.63	7.05	0.682	0.81	1.32	7.30	1.82
10-12-77	1115	Cation effluent	1.55	2.1	0.009	0.04	0.07	0.021	0.02	1.21	0.107	3.65
10-12-77	1115	Anion effluent	0.18	<0.1	<0.001	<0.01	0.01	0.0002	<0.01	0.019	0.018	15.5
10-12-77	1140	Raw AMD	0.01	0.4	<0.001	0.01	0.02	<0.0002	0.17	<0.001	0.266	0.80
10-12-77	1140	Spiked AMD	3.12	2.3	1.19	0.78	8.90	0.795	1.03	1.62	8.97	1.49
10-12-77	1140	Cation effluent	1.44	2.1	0.021	0.04	0.09	0.019	0.03	1.21	0.145	1.81
10-12-77	1140	Anion effluent	0.10	0.2	0.003	<0.01	0.04	0.0002	0.01	0.012	0.016	16.5
10-12-77	1255	Cation regener.	2.48	1.5	0.177	0.18	1.86	0.346	0.25	1.03	2.04	16.5
10-12-77	1311	Cation regener.	2.11	2.5	2.20	1.31	23.3	0.073	3.01	0.642	23.9	3.60
10-12-77	1327	Cation regener.	1.14	1.9	1.27	0.44	12.4	0.190	1.66	0.494	12.9	0.98
10-12-77	1345	Cation regener.	1.01	2.0	0.746	0.23	7.08	0.205	1.04	0.520	7.52	1.40
10-12-77	1430	Anion regener.	1.50	1.9	0.023	0.04	0.19	0.178	0.09	0.642	0.368	1.22
10-12-77	1435	Anion regener.	0.40	2.0	0.045	0.07	0.20	0.068	0.45	0.316	1.30	1.28
10-12-77	1440	Anion regener.	0.19	2.1	0.030	0.03	0.13	0.018	0.29	0.165	0.782	1.27
10-12-77	1445	Anion regener.	2.23	2.9	<0.001	0.07	0.14	0.025	0.45	2.51	0.148	31.9
10-12-77	1520	Raw AMD	0.01	0.7	<0.001	0.04	0.03	<0.0002	0.16	<0.001	0.271	0.86
10-12-77	1520	Spiked AMD	2.42	2.9	0.771	0.50	5.77	0.687	0.69	1.32	5.91	1.50
10-12-77	1520	Cation effluent	1.53	2.0	0.010	0.04	0.10	0.119	0.02	0.980	0.108	22.8
10-12-77	1520	Anion effluent	1.88	1.7	<0.001	0.03	0.06	0.008	0.06	0.430	0.057	4.55

(continued)

TABLE C-7. (Continued)

Date	Time	Sample	As	B	Cd	Cr	Cu	Hg	Ni	Se	Zn	P
10-12-77	1605	Raw AMD	0.02	0.6	0.003	0.01	0.04	<0.0002	0.15	<0.001	0.257	0.86
10-12-77	1605	Spiked AMD	2.50	2.7	0.985	0.64	7.68	0.804	0.88	1.47	7.82	1.42
10-12-77	1605	Cation effluent	1.84	2.6	0.253	0.04	0.09	0.078	0.01	1.12	0.099	3.81
10-12-77	1605	Anion effluent	0.63	0.3	<0.001	<0.01	0.03	0.0005	<0.01	0.067	0.035	11.2
10-12-77	1650	Raw AMD	0.03	0.7	<0.001	0.01	0.02	<0.0002	0.18	<0.001	0.317	0.28
10-12-77	1650	Spiked AMD	2.96	2.4	0.934	0.64	7.16	0.804	0.85	1.65	7.47	1.45
10-12-77	1650	Cation effluent	1.89	2.4	0.011	0.09	0.06	0.108	0.02	1.38	0.103	4.35
10-12-77	1650	Anion effluent	0.31	0.4	<0.001	<0.01	0.01	0.0003	0.01	0.019	0.023	1.68
10-12-77	1745	Raw AMD	<0.01	0.7	<0.001	0.01	0.02	<0.0002	0.19	<0.001	0.339	0.22
10-12-77	1745	Spiked AMD	1.31	2.5	0.922	0.59	7.26	0.750	0.90	0.768	7.53	0.77
10-12-77	1745	Cation effluent	2.0	2.4	0.013	0.07	0.10	0.186	0.01	1.30	0.121	2.29
10-12-77	1745	Anion effluent	0.10	0.4	<0.001	<0.01	0.01	0.0005	0.01	0.014	0.015	4.80
10-12-77	1905	Cation regener.	2.31	2.1	1.87	1.21	15.5	0.366	1.97	0.621	14.9	0.95
10-12-77	1920	Cation regener.	1.62	1.8	2.28	0.86	20.5	0.122	2.62	0.464	20.2	0.37
10-12-77	1935	Cation regener.	1.05	2.0	0.909	0.35	11.0	0.259	1.45	0.481	11.1	0.30
10-12-77	1950	Cation regener.	0.98	2.1	1.11	0.33	10.1	0.337	1.36	0.490	9.96	0.76
10-12-77	2025	Anion regener.	0.46	2.1	0.080	0.10	0.30	0.100	0.52	0.318	1.66	2.02
10-12-77	2030	Anion regener.	0.25	2.2	0.035	0.04	0.11	0.013	0.28	0.165	0.778	1.49
10-12-77	2035	Anion regener.	0.47	2.2	0.003	0.05	0.09	0.013	0.37	0.630	0.289	1.28
10-12-77	2040	Anion regener.	11.4	5.6	<0.001	0.08	0.10	0.063	0.47	11.2	0.099	2.69
Mean		Raw AMD	0.01	0.6	0.001	0.02	0.03	0.0002	0.18	<0.001	0.351	0.74
Std.dev.		Raw AMD	0.01	0.15	0.00	0.012	0.016	-0-	0.014	-0-	0.141	0.40
Mean		Spiked AMD	2.47	2.38	0.945	0.63	7.27	0.723	0.86	1.34	7.44	1.47
Std.dev.		Spiked AMD	0.55	0.30	0.119	0.077	0.861	0.082	0.096	0.27	0.84	0.39
Mean		Cation effluent	1.68	2.2	0.042	0.05	0.11	0.074	0.02	1.19	0.135	8.86
Std.dev.		Cation effluent	0.20	0.30	0.085	0.019	0.052	0.060	0.006	0.13	0.051	8.23
Mean		Anion effluent	0.52	0.58	<0.001	0.01	0.03	0.0013	0.02	0.088	0.034	9.71
Std.dev.		Anion effluent	0.58	0.58	0.001	0.01	0.026	0.0027	0.018	0.14	0.023	5.54
Mean		Cation regener.	1.59	2.0	1.32	0.61	12.7	0.237	1.67	0.593	12.8	3.13
Std.dev.		Cation regener.	0.63	0.29	0.74	0.45	7.0	0.108	0.87	0.19	6.9	5.50
Mean		Anion regener.	2.11	2.6	0.027	0.06	0.16	0.05	0.37	2.00	0.678	5.39
Std.dev.		Anion regener.	3.82	1.24	0.023	0.02	0.07	0.057	0.14	3.80	0.565	10.7

TABLE C-8. ION EXCHANGE CONVENTIONAL POLLUTANT ANALYSES

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Cation Equiv.
10-12-77	1000	Raw feed	2600	460	5.5	350	100	150	150	400	4.0	3.7	2340	40	3350	0.7	2460
10-12-77	1000	Spiked feed	2600	460	5.3	350	100	150	140	400	4.0	3.7	2330	30	3340	0.5	2470
10-12-77	1000	Cation effluent	10000	2600	1.8	10	2.7	2.2	2.2	50	.12	.08	890	0	960	1.7	150
10-12-77	1000	Anion effluent	1400	0	11	4.6	4.0	.05	0	400	.12	.05	380	560	790	5.9	900
10-12-77	1045	Raw feed	2600	430	5.5	340	100	150	144	400	4.0	3.8	2350	45	3340	2.0	2440
10-12-77	1045	Spiked feed	2600	430	5.3	340	100	150	142	400	4.0	3.8	2330	25	3320	0.2	2440
10-12-77	1045	Cation effluent	10000	2690	1.8	10	2.5	2.0	2.0	50	.20	.06	980	0	1050	7.7	150
10-12-77	1045	Anion effluent	600	0	9.8	12	2.1	.05	0	170	.20	.05	150	250	330	1.6	400
10-12-77	1115	Raw feed	2600	440	5.5	350	100	150	140	400	4.0	3.9	2350	45	3350	0.9	2460
10-12-77	1115	Spiked feed	2600	440	5.3	350	100	150	140	400	4.0	3.9	2330	25	3330	0.8	2460
10-12-77	1115	Cation effluent	10000	2690	1.8	10	2.6	2.0	2.0	50	.20	.05	980	0	1050	7.7	150
10-12-77	1115	Anion effluent	380	0	9.5	8.8	1.85	.05	0	100	.20	.05	150	200	260	30	250
10-12-77	1140	Raw feed	2700	410	5.4	350	100	150	150	400	4.2	3.9	2340	40	3350	0.7	2460
10-12-77	1140	Spiked feed	2700	430	5.2	350	100	150	140	400	4.2	3.9	2480	15	3490	5.0	2460
10-12-77	1140	Cation effluent	9600	2400	1.8	13	3.0	2.6	2.6	150	.26	.12	1000	0	1170	10.9	380
10-12-77	1140	Anion effluent	330	0	9.0	9.6	2.2	.05	0	80	.05	.05	200	150	290	42	210
10-12-77	1255	Cation effluent	4200	770	2.4	150	50	68	66	600	3.4	2.0	1980	0	2850	8.2	2040
10-12-77	1311	Cation effluent	27000	4430	1.5	730	520	814	800	2000	40	30	11400	0	15530	1.8	10060
10-12-77	1327	Cation effluent	60000	19410	1.1	1000	300	430	430	760	16	8.0	14050	0	16570	30.0	6280
10-12-77	1345	Cation effluent	70000	22270	1.1	700	200	300	300	385	10	6.1	7830	0	9430	1.9	4020
10-12-77	1430	Anion effluent	9000	2640	1.5	20	4.2	20	19	55	.50	.40	1700	0	1800	2.1	230
10-12-77	1435	Anion effluent	2500	810	2.0	35	7.3	50	44	80	.90	1.0	820	0	1800	4.5	390
10-12-77	1440	Anion effluent	1600	500	2.5	35	7.4	40	40	170	.48	.95	690	0	940	1.3	560
10-12-77	1445	Anion effluent	23000	460	3.5	45	5.5	20	20	9200	.60	.50	18850	0	28120	3.2	20230
10-12-77	1520	Raw feed	2700	420	5.4	350	100	150	150	380	5.2	3.7	2330	25	3310	1.5	2410
10-12-77	1520	Spiked feed	3000	550	3.0	350	100	150	150	380	5.2	3.7	2470	0	3450	4.0	2410
10-12-77	1520	Cation effluent	10100	2790	1.8	10	2.5	2.1	2.1	50	.28	.08	980	0	1050	7.6	150
10-12-77	1520	Anion effluent	5600	0	12	.19	.06	.05	0	1400	.48	.05	3200	390	4600	17.7	3060

(continued)

TABLE C-8 (Continued)

Date	Time	Sample	Cond	Acid	pH	Ca	Mg	Total Fe	Fe^2	Na	Al	Mn	SO_4	Alk	TDS	Ion* Bal	Cation Equiv.
10-12-77	1605	Raw feed	2800	460	5.5	350	100	170	160	360	5.6	3.8	2490	25	3470	4.9	2410
10-12-77	1605	Spiked feed	2800	480	5.1	350	100	160	150	350	5.6	4.0	2320	15	3290	1.9	2380
10-12-77	1605	Cation effluent	11000	2720	1.8	10	2.5	2.0	2.0	45	.22	.12	980	0	1040	8.8	140
10-12-77	1605	Anion effluent	850	0	10	14	2.5	.05	0	220	.24	.05	200	390	440	11.2	530
10-12-77	1650	Raw feed	2800	560	5.2	350	100	200	180	350	8.8	4.2	2480	10	3480	4.5	2470
10-12-77	1650	Spiked feed	2800	560	4.7	350	100	200	180	340	8.8	4.2	2470	5	3470	4.9	2450
10-12-77	1650	Cation effluent	11000	2670	2.0	10	2.5	1.9	1.5	45	.16	.08	650	0	710	5.6	140
10-12-77	1650	Anion effluent	380	0	9.6	9	1.8	.05	0	100	.06	.05	100	150	210	2.2	250
10-12-77	1745	Raw feed	2800	600	4.9	350	100	200	190	330	10	4.3	2470	8	3470	5.5	2440
10-12-77	1745	Spiked effluent	2800	620	4.5	350	100	200	190	330	10	4.3	2470	0	3460	4.7	2440
10-12-77	1745	Cation effluent	10000	2570	2.0	12	2.8	2.0	2.0	130	.20	.12	800	0	950	1.9	320
10-12-77	1745	Anion effluent	350	0	8.6	11	2.7	.05	0	150	.16	.05	220	170	390	8.7	370
10-12-77	1905	Cation effluent	12150	3160	2.1	800	350	500	500	1400	17	9.0	7540	0	10620	0.8	7500
10-12-77	1920	Cation effluent	50000	15770	1.3	870	400	590	580	1000	20	25	10730	0	13640	12.9	7220
10-12-77	1935	Cation effluent	64000	16110	1.2	930	280	420	400	500	13	6.8	9100	0	11250	9.4	5420
10-12-77	1950	Cation effluent	69000	16910	1.2	700	200	320	310	310	10	5.8	7030	0	8580	3.5	3900
10-12-77	2025	Anion effluent	2700	740	2.0	42	8.6	60	50	80	1.0	1.1	950	0	1140	6.9	420
10-11-77	2030	Anion effluent	2500	370	2.6	40	8.6	40	40	510	.46	.94	1480	0	2080	5.7	1320
10-12-77	2035	Anion effluent	17000	470	3.5	62	12	26	22	6250	.10	.88	14770	0	21120	9.5	13880
10-12-77	2040	Anion effluent	28000	410	3.7	30	3.8	6.0	5.4	12000	.66	.38	24550	0	36590	2.8	26270
Mean		Raw feed	2700	470	5.4	350	100	170	160	380	5.7	3.9	2390	30	3390		
		Spiked feed	2740	500	4.8	350	100	160	140	380	5.7	3.9	2400	14	3340		
		Cation effluent	21580	2640	1.9	11	2.6	2.1	2.1	71	.20	.09	910		1000		
		Anion effluent	1240	0	9.9	8.7	2.2	.05	0	330	.19	.05	580	280	900		

All units are mg/l except for pH, specific conductance (μmhos/cm), and ion balance (expressed as a percent difference between cations and anions as $CaCO_3$). Cation equivalents are expressed as $CaCO_3$.

GLOSSARY

ION EXCHANGE TERMINOLOGY

anion: A negatively charged ion (e.g., OH^-, SO_4^{-2}, CO_3^{-2}).

cation: A positively charged ion (e.g., Na^+, Fe^{+2}, Al^{+3}).

dosage rate: Also called regeneration level, it is the amount of regenerant chemical (expressed as 100 percent-concentration and converted to calcium carbonate equivalence) per volume of resin in the ion exchange column. The dosage rate is commonly expressed in grams (of 100% regenerant) per liter of resin or 16/cu ft.

exchanger capacity: The actual total of ions (expressed as $CaCO_3$) exchanged during the service cycle. This is always less than the theoretical capability described by the dosage rate. Exchanger capacity is commonly expressed as grams (as $CaCO_3$) per liter of resin or grains/cu ft.

ion exchange: A reversible exchange of ions between a solid and a liquid in which there is no substantial change in the solid. The solid is the ion exchange resin.

regenerant: A solution containing a high concentration of suitable ions used to convert (or regenerate) an ion exchange resin to the desired ionic form (e.g., H_2SO_4 supplies H^+ ions to regenerate strong-acid cation resins to the H^+-form).

regenerant utilization efficiency: The ratio of regenerant chemical utilized as compared to the amount added to regenerate the resin, expressed as a percentage. This is calculated by dividing the exchanger capacity by the dosage rate.

strong-acid cation resin: A resin, which when regenerated with acid, will exchange hydrogen ions (H^+) for cations present in the influent according to $FeSO_4 + 2H^+ \cdot R \rightleftarrows Fe^{+2} \cdot 2R + H_2SO_4$.

weak-base anion resin: A resin unable to split neutral salts but which absorbs free acid, according to $R + H_2SO_4 \rightarrow R \cdot H_2SO_4$.

REVERSE OSMOSIS TERMINOLOGY

brine: The waste solution resulting from reverse osmosis separation of an influent into product and brine (also called concentrate).

flux: The rate of water permeation through the reverse osmosis membrane, usually expressed in liters/sq m/day (or gal/sq ft/day) at a specified temperature and pressure. The flux rate is strongly dependent upon temperature, applied pressure, and osmotic pressure. In this report, the pressure specified in the net driving pressure (i.e., applied pressure minus osmotic pressure).

osmotic pressure: The pressure at which the permeation rates from the brine side of the membrane to the product side and vice versa are in equilibrium. The osmotic pressure is a characteristic of the chemical composition of the influent and is strongly related to concentration. When the applied pressure exceeds the osmotic pressure, dewatering begins. Osmotic pressure is usually expressed in g/sq cm or psi.

recovery: The percentage of the raw water fed to the reverse osmosis unit that results as product.

reverse osmosis: Flow through a semipermeable membrane where the direction of flow is from the concentrated solution to the dilute solution. Such a flow is induced by pressure applied to the concentrated solution.

salt rejection: A measure of a membrane's ability to selectively allow pure water to pass through but reject the passage of impurities; a measure of a membrane's impermeability with respect to salts; usually expressed as a percentage:

$$\frac{(\text{Influent Quality} - \text{Product Quality})}{(\text{Influent Quality})} \times 100.$$

NEUTRALIZATION TERMINOLOGY

material balance: A calculation to compare inputs and outputs of a chemical system using |flow in x concentration in = flow out x concentration out|.

stoichiometric factor: The ratio of amount of neutralizer required to treat original amount of acid present:

$$\text{Stoichiometric factor} = \frac{\text{Alkalinity added (as } CaCO_3)}{\text{Influent acidity (as } CaCO_3)}$$

utilization efficiency: A measure of the proportion of a neutralizer that reacts with the acid water as compared to the amount originally added. Since alkalinity imparted to the water is considered a benefit, the formula for utilization efficiency is:

$$\text{Utilization efficiency} = \frac{\text{Alkalinity used}}{\text{Alkalinity added}}$$

therefore,

$$\text{Utilization efficiency} = \frac{\left[\begin{array}{l}\text{Influent acidity - effluent acidity +} \\ \text{Effluent alkalinity (all as } CaCO_3)\end{array}\right]}{\text{Alkalinity added (as } CaCO_3)} \times 100$$